UNITED STATES DEPARTMENT OF AGRICULTURE

BULLETIN No. 835

Contribution from the Bureau of Public Roads
THOMAS H. MACDONALD, Chief

Washington, D. C. PROFESSIONAL PAPER August 6, 1920

CAPILLARY MOVEMENT OF SOIL MOISTURE

By

WALTER W. McLAUGHLIN, Senior Irrigation Engineer

CONTENTS

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By WALTER W. McLAUGHLIN, *Senior Irrigation Engineer.*

CONTENTS.

The irrigation engineer has long felt the need of more detailed information as to the importance of capillarity as a source of loss of water from irrigation works and the part it plays in distributing, within the soil, water applied in irrigation. It has long been recognized that impounding reservoirs and conveying channels lose more water than can be accounted for by direct percolation and evaporation. Whether this loss was the result of capillary action alone or in combination with the transpiration from plant growth along canal banks has been only a matter of conjecture. Where the water applied to soil by irrigation goes and how it ultimately distributes itself within the soil have been questions of speculation.

It has been observed that the percentage of moisture determined in the field in the usual way has not always given a true basis upon which to determine the necessity of applying water by irrigation. In some instances, the percentages of moisture determined have been above the wilting point and yet plants were wilted.

This condition has caused the irrigation engineer to speculate upon the probability of the rate of movement of soil moisture from one point to another by capillarity, as well as the extent to which the moisture may move.

The irrigator is always confronted by questions of methods of irrigation, duration of irrigation, and frequency of irrigation. The

first aim is to obtain a uniform distribution of moisture within reach of the plant roots and to maintain such distribution. The economical application of water to prevent waste from deep percolation or surface run-off and to maintain an optimum percentage of moisture within the soil is the vital problem. For instance, under specified soil and topographic conditions, how long should the furrows be and how far apart? With turns of irrigation coming at specified intervals, how much water should be applied and how long should an irrigation be continued at each turn? To approximate an accurate answer to questions of this kind it is necessary to know more accurately than we now know the rate and extent of movement of the soil moisture by capillarity during the several periods of an irrigation season.

The drainage engineer in the arid region has frequently been perplexed by a condition of water-logging under conditions which seem to preclude the possibility of the movement of free water as such from any known source to the wet area. He has often felt a want of specific information which would indicate the development of free water from capillary moisture and the importance of this form of moisture in farm drainage.

OBJECT.

As a basis for answering some of the above questions investigations were undertaken in 1915, and the data given below are in the form of a progress report.

The object of these experiments is to furnish specific data as to the capillary movement of moisture in the soils of the arid region. It is felt that these will be of prime importance to the irrigation engineer in the proper construction and operation of conveying channels and impounding reservoirs, and that they will enable him to point out the most economical methods of applying water to fields. These data were obtained for different soils and under different conditions.

PLAN OF EXPERIMENTS.

Because it was realized that the rate and extent of movement of moisture in soils by capillarity differs materially where the source of moisture is a body of free water from where it is a body of wet soil, the experiments have been divided into two parts:

1. Where the source of the moisture is a body of free water into which the soil column extends.

2. Where the source of moisture is a body of soil containing a percentage of moisture greater than the wilting percentage, and not connected with a body of free water.

The work as planned and carried out embodied a study of the rate and extent of capillary movement of moisture in columns of various types of soil, where capillarity was assisted by gravity, where it acted against gravity, and where gravity as a factor was eliminated.

The columns in which gravity was to assist capillarity were inclined downward at various angles from the horizontal; the columns in which gravity was to act against the force of capillarity were inclined upward at various angles from the horizontal; and the columns in which the effect of gravity was to be eliminated as far as possible were set horizontal.

Inasmuch as evaporation is one of the factors that controls the extent and rate of movement of soil moisture by capillarity, it was decided to run each set of experiments in duplicate, except that one column was to be covered on all sides and evaporation reduced to a minimum, while the other column was to be uncovered and exposed on one side to the air.

It was essential to the plan of the experiments that the probability of free water as such entering the columns be reduced to a minimum and yet have sufficient water enter the flumes to give something with which to work. It was desired to have a high initial percentage of capillary water, and at the same time eliminate free water. To accomplish this end it was decided to have a vertical lift from the surface of the water in the tank to the bottom of the container of the soil column proper of from 3 to 4 inches. After several preliminary tests a vertical lift of 4 inches was adopted and all columns except the vertical ones (unless otherwise stated) have a vertical "lift" of 4 inches from the surface of the water in the tanks to any change in direction of the column. That part of the soil column from the surface of the water to the point of change in direction has been termed the "wick" in the discussion which follows.

Air-tight joints were maintained and no water escaped from the tanks except by the wick and no moisture from the columns except by evaporation. To guard against the formation of a true siphon within the soil column an air space was maintained upon at least one side of the soil column throughout its entire length, in the columns inclined downward.

All water added to the tanks after the initial filling was measured and recorded. At specified intervals the position of the outward extent of the wet area of soil was measured and these measurements recorded.

The experiments in which a moist soil was the source of moisture rather than a body of free water differ but little from those described, except that evaporation was eliminated in all cases.

The soil boxes were partially filled with a soil containing a known percentage of moisture, greater than the wilting percentage, and the

remainder of the box filled with air-dry soil packed firmly against the wet soil. The boxes were set either vertical or horizontal, no inclined boxes being used. In the boxes set vertical, in some experiments, the wet soil was placed at the top of the box and the air-dry soil was placed at the lower end. In other boxes the wet soil was placed at the lower end of the box and the air-dry soil at the upper end. Thus, the movement of the moisture from the wet soil into the dry soil by capillarity would be, in some cases, with the force of gravity and, in other cases, in an opposite direction. A few vertical boxes had the middle section of the box filled with the wet soil, with the air-dry soil at both ends, thus combining in the same box and at the same time the upward and downward movements.

The horizontal boxes were packed in the same way as the vertical boxes with wet soil at one end and air-dry soil at the other. In a few tests the middle section of the horizontal boxes was filled with wet soil and air-dry soil placed at both ends. In a very few tests the middle part of the box was filled with two sections of wet soil containing different initial precentages of moisture and the dry soil was placed at both ends of the box.

METEOROLOGICAL DATA.

In connection with the experiments a record was kept of the evaporation from a free water surface and a thermograph record taken of the air temperature. No other meteorological data were recorded.

SOILS USED.

A uniform surface soil was selected for each set of experiments. This soil was to be typical of a large area and was to be of a well-known type. The soils were to be obtained from various parts of the arid region that the data might be of general value. The greater the number of types and the wider the range in types of soils used, the greater the value of the tests. Uniform soils were to be used, as the movement of moisture by capillarity varies in soils of different types and the results obtained with mixed soils would be of little value.

INCIDENTAL EXPERIMENTS.

The movement of soil moisture by capillarity within a soil of a uniform type differs materially from its movement between soils of different types. This difference is found in the rate and extent of movement and in the initial percentage of moisture necessary to permit movement. To obtain some light upon this point a few experiments were conducted. The general plan of these auxiliary experiments was about the same as for the original experiments. In

the auxiliary experiments, various types of soil were packed in layers or one end of a column or box contained soil of one type and the other end soil of a different type.

METHOD AND EQUIPMENT.

A confined soil column was used and the method differed from that usually employed by other investigators only in the size and arrangement of soil columns. The columns used in these experiments are 100 square inches in cross-sectional area and much larger than the columns usually employed. A feature made important in the present work is the use of inclined columns.

One side and the bottom of each flume were made of wood with metal lining and the other side was of plate glass. In the discussion of the experiments the term "flume" will be used to designate the soil column and its container.

Uniform soil was packed into the flumes and wicks extended from within the water in the tanks up into the flumes. After the soil had been placed in the flumes the tanks were filled up to the initial level and this level rather constantly maintained throughout the experiment.

At 9 a. m. of each day and frequently at other hours the outward extent of the soil wetted by capillary moisture was measured, and the water in the tanks was brought up to the initial elevation with measured quantities of water added directly to the tanks. Soil samples were taken at various points in the wet soil area, at such intervals of time as deemed advisable and always at the end of an experiment. All the flumes or columns were protected by canvas from the direct rays of the sun and from the rain.

MEASURING THE ADVANCE OF THE CAPILLARY MOISTURE.

The outward extent of the wetted soil area, indicating the extent of the moisture movement at any time, is plainly visible through the glass side of the flume. The wetted soil is of a darker color and the line of demarcation is very distinct. The position of this line as seen through the glass side was traced upon the glass. The position of these markings with reference to the surface of the water in the tank is determined by five direct measurements made in the way and to the points as follows:

Five lines are drawn along the glass side of the flume parallel to the longitudinal axis of the flume. The first line is at the top of the glass; the second line is $2\frac{1}{2}$ inches lower; the third is 5 inches from the top and at the middle of the glass side; the fourth is $7\frac{1}{2}$ inches from the top, while the fifth is at the bottom of the flume and 10 inches from the top line. The intersections of the marks on

the side of the flume indicating the outward extent of the wet soil area and the five lines above described give five definite points with which to locate each of the markings upon the glass side of the flume. The positions of these five points are determined by direct measurements from the surface of the water in the tank along the five lines parallel to the longitudinal axis of the soil column.

The original horizontal surface of the water in the tanks was used as a base for all measurements of the position of the moisture in the soil column in all flumes rather than a transverse line coincident with the change in inclination of the soil column, if any, from the vertical. Inasmuch as the movement of moisture in the soil columns by capillarity from free water is about equal for all inclinations, from the vertical upward to the vertical downward, for the first foot or more, using the surface of the water as a base for measurements does not produce an appreciable error in making comparisons.

In the experiments with wet and dry soils the initial point of measurement is the line of contact between the original areas of wet and dry soil. No water is added to the boxes after they are set up, but the water is added to the wet soil at the time of packing. The quantity of water to be added to the soil to be packed wet is calculated upon the dry weight of the soil and then this water is added by measurement.

MAINTAINING THE WATER LEVEL IN TANKS.

All water added to the tanks after the initial filling is added in measured quantities and recorded as water used by the flume. Water is added sufficiently often to maintain the level of water in the tanks at a rather constant elevation. The water added during any 24 hours is recorded as the water used during the day ending at 9 a. m. Unless otherwise specified all references to water used per day will mean for the day ending at 9 a. m.

SAMPLING FOR MOISTURE.

The soil is sampled for moisture with a ¾-inch carpenter's auger in the usual way and the samples immediately placed in tared screw-topped glass bottles and weighed. A composite sample is made of the upper 5 inches of soil and another composite sample for the lower 5 inches in each boring. The samples are taken in planes parallel to the planes indicating the advance of the moisture within the flumes at the points sampled. A boring is located by a measurement along the top of the flume from the water level. The samples, as soon as convenient after the first weighing, are placed in a water-jacketed oven and dried at the temperature of boiling water until a constant weight is obtained. Using the dry weight of the soil sample as a basis, the percentage of moisture in the sample is calculated.

The samples from the box experiments are taken and treated in the same way as for the flumes, except that one composite sample is made for each boring in the boxes.

PREPARATION OF SOIL FOR PACKING.

The soil to be used in the experiments is thoroughly air dried, if not already so. The soil is spread out in thin layers and exposed to the direct rays of the sun for several days. The air-dried soil is then screened through a $\frac{1}{2}$-inch screen and all large rocks, roots, etc., removed. Lumps of soil are broken up and screened. The heavy clay soils having numerous large lumps are rolled with a hand lawn roller and screened. In order that the soil grains may not be broken by the roller, it is necessary to roll upon some rather yielding foundation. A soil foundation was made by rolling repeatedly with a weighted roller. Soils of the clay and loam type are passed through a 14-mesh screen and the screenings from all operations thoroughly mixed. The preparation of the heavier soils of the Whittier type is a slow and tedious operation. It is only by repeated rolling with a light roller that the soils can be properly fined without crushing the soil grains.

SETTING UP THE FLUMES.

The flumes were set up out in the open and were protected only from the direct rays of the sun and from the rain. They rest upon 2 by 12 inch plank cut to the proper length and set upon end. The tanks rest upon small stands fastened firmly to the foundation for the flumes. Thus the supporting structure for the entire soil column is rigid.

The flume, tank, and ell were set in position, the glass side of the flume put in position, and then all joints were filled with melted paraffin wax. All joints were tested a second time to see that they were air and water tight. The flume including the wick was then ready for packing.

PACKING SOIL IN FLUMES.

The soil was placed in the flume in 2-inch layers and packed with a wooden block and hammer. The block is corrugated and is 4 by 6 inches. The packing was done by striking the block with the hammer, using as uniform a blow as practicable and continuing the packing until the soil was of about the same density as found in the field. This density was estimated in both instances by measurement and weight. The soil was placed and packed into the flumes layer by layer until filled.

PACKING THE BOXES.

The boxes were packed with soil in much the same way as the flumes, except when the initial percentage of moisture in the wet-soil part of the box was relatively low. In this case, the soil was first wetted to the desired degree, and then placed in the box in layers one inch thick and packed by dropping a weight a given distance upon a board covering the layer of soil. The distance the weight was to be dropped, and the number of times it was to be dropped for each layer was determined by tests for each soil. The section of the box to be filled with air-dry soil was packed by using the hammer and block.

PREVENTING EVAPORATION IN FLUMES.

Those flumes in which evaporation from the top of the flume was to be prevented were covered with two-ply unsanded maltoid roofing paper. A strip of the roofing cut to the proper size was placed upon the top of the flume and reached from one end to the other. The side joints were made air tight. On the glass side of the flume the roofing was folded over and down on the outside of the glass about one-half inch. The joint between the roofing and the glass was held in place and made tight by means of an angle-iron strip made of galvanized iron clamped along the upper edge of the glass and on top of the roofing. To prevent air-trapping, $\frac{1}{4}$-inch vent holes were cut in the roofing at intervals of about 4 feet. Tests of the effectiveness of this covering to prevent evaporation of moisture from the flumes indicate that at least 80 per cent of the evaporation from an open flume was prevented by this covering.

A more effective method of preventing evaporation could be devised, but there would be great danger of the entrance of some unknown factors into the work. The entrance of these factors would prove fatal for comparison with much of the other work.

COVERING THE BOXES.

The plate-glass sides of the boxes were sealed to the boxes by means of cushions made of maltoid roofing. The glass was held in place and clamped tightly to the box by means of wooden strips fastened to the box proper by means of eyebolts fitted with thread and nut. Rubber cushions were tried, but did not give the same satisfaction that was obtained from the use of maltoid.

CAPILLARY ACTION IN THE SOIL IN THE ABSENCE OF FREE WATER.

The term "free water" as here used is water not held by capillarity and obeying the laws of gravity. It is variously termed "free water," "ground water," and "water of gravitation." (17.)[1]

[1] The figures in parentheses apply to the references at the end of this bulletin.

The plan of this experiment was to study the rate and extent of movement of moisture from a wetted soil into an air-dry soil when the two were brought in contact. The wetted soil was to contain various percentages of moisture from near the point of capillary saturation down to the wilting point.

THE SOIL BOXES.

The soil boxes or soil tubes for this work as first designed consisted of galvanized iron boxes 6 by 6 inches in cross section and of various lengths from 4 to 8 feet.

It was soon found that the metal boxes first used were not sufficiently rigid. They were difficult to pack and the least jarring of the box after it was packed and set in position was very apt to crack the soil column. The second set of equipment, the boxes now in use, is described later.

ADDING THE WATER.

Various methods were tried for adding the water to soil to be wetted and at the same time insure a uniform pack offering no mechanical obstacle in the movement of the moisture by capillarity. The method finally adopted as giving the most uniform results for the higher percentages of moisture was found not adapted to the smaller percentages of moisture. In the first method, the water was added to the soil after it had been packed and its distribution in that part of the soil column left to capillary action. In the second method, or the one used for the smaller percentages of moisture, the water was added before packing. Where the water was to be added after the soil was packed, a small furrow about 2 inches deep was made the entire length of the part of the column to be wetted and the proper amount of soil would take it up, and finally, with the last of the water was added that part of the soil removed to make the furrow. The wetted soil was then covered with plate glass and allowed to stand 24 hours before packing the air-dried part of the column. As soon as the dry soil was added the plate glass side was placed and sealed in position and the box set in place and the experiment was under way.

When the moisture was added before packing, a mass of soil sufficient for one pack was moistened to the desired percentage by adding a weighted quantity of water. The mass was thoroughly mixed by turning over and over several times on a piece of oil cloth. This soil was then placed in the box in layers 2 inches in thickness and tamped with a hard rubber tamping bar. The amount of tamping was much a matter of judgment and testing, except that the same

soil with the same percentage of water used in different boxes received the same amount of tamping.

MEASURING THE ADVANCE OF MOISTURE.

The change in color of the soil in the dry part of the column with a change in moisture content was very marked in nearly all soils except the light sands, devoid of much organic matter. With the position of the contact of the wet and dry part of the column at the commencement of the experiment marked upon the glass side of the box, it was a simple matter to measure the distance the moisture had moved into the dry part of the column at any time. These measurements were recorded, as well as the date and hour of the measurement.

OTHER OBSERVATIONS OF THE SOIL COLUMN.

During an experiment and at its expiration close observations were made of the condition of the column for cracks or other factors that might influence the ultimate results. At the end of the experiment observations were made at the outer extremity of the apparent wetted area in the original dry part of the box to determine if the advance of the moisture had been the same in all parts of the column. In many cases it was found that the extent of the movement was a little greater upon one side of the column than upon the other. These differences were probably caused by differences in temperature rather than lack of uniformity in packing.

PROTECTION FROM SUN AND RAIN.

To protect the flumes from the direct rays of the sun and from the rain, canvas covers were provided. These covers were held away from the sides of the flumes and from the top by iron bows and iron strips similar to the old-fashioned wagon cover. This provided ready circulation of air and ample protection from the weather. Inasmuch as each flume was protected in this way no corrections had to be made for the exposure of the flumes to the sun's rays due to differences in angles of inclination or their setting in reference to the compass. Figure 1 shows the tank ell or wick and a section of flume as they appear when in position for filling.

THE TANKS.

The tanks used to contain the water from which the soil columns obtain moisture are made of galvanized iron. They are 12 by 20 inches in area and 8 inches deep. Near the bottom and at one end of each tank is fitted a $\frac{5}{8}$-inch water-gage glass, extending upward upon the outside of the tank, so that the height of the water in the

tank can be determined after the lid is placed in position. Around the outside and at the top of the tank is soldered a galvanized iron channel, three-eighths inch wide and three-quarters inch in depth. This channel is to receive the edge of the cover to the tank.

The lid of the tank is of material similar to the tank and has the outer edge turned down three-quarters of an inch all the way around to fit into the channel on the tank. Passing through the lid and

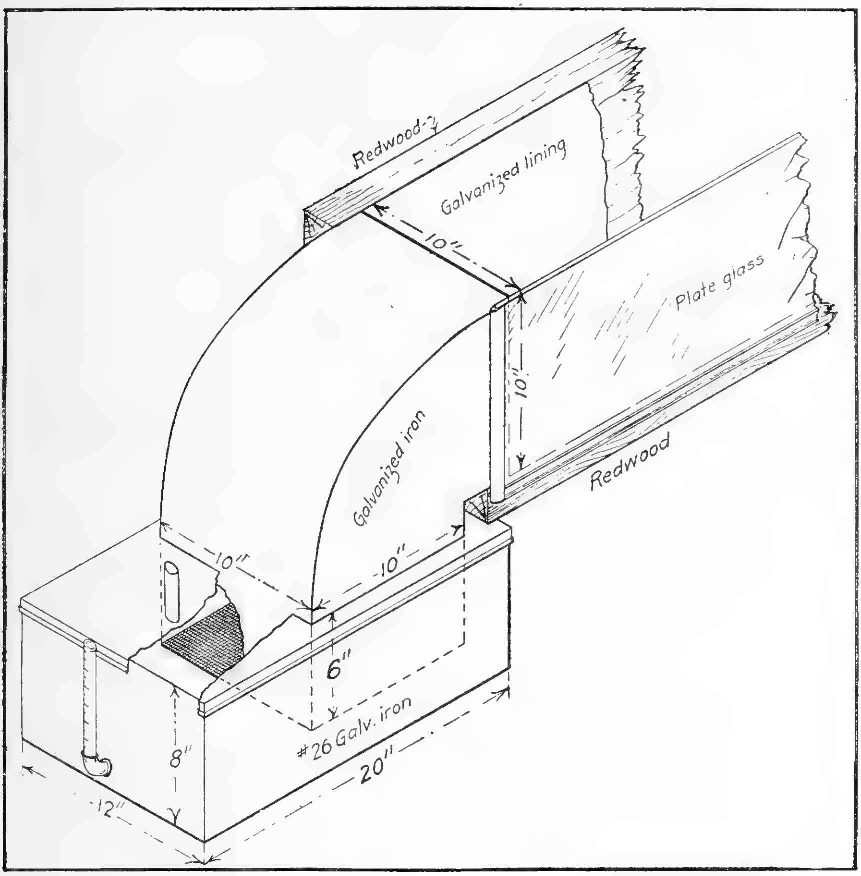

Fig. 1.—Isometric view of open flume connected by wick to supply tank.

soldered to it is the ell. Into the lid is fitted a $\frac{3}{4}$-inch tube through which water may be added to the tank. To support the weight of the ell and to stiffen the lid, two galvanized-iron channels are riveted to the underside of the lid, running crosswise of the tank. These channels are placed just outside the ell.

THE ELL.

The ell is, as the name implies, an elbow used to change the direction of the soil column from the vertical. It extends 6 inches

within the tank and a few inches within the flume proper. The ell is made of galvanized iron and has a cross-sectional area of 100 square inches. The bottom end of the ell is closed with a piece of very fine meshed brass-wire gauze soldered to the ell. The angle of the ell is made sufficient to change the direction of the soil column from the vertical upward to any specified angle. The angles used varied from 45° up to 45° down.

THE FLUME.

The flume proper is that part of the equipment designed to hold that part of the soil column extending beyond the outer end of the ell. The bottom and one side of each flume are made of 2-inch redwood plank lined with galvanized iron. The second side of the flume is of plate glass, while the top of the flume is open or covered with maltoid roofing. The flumes are 10 by 10 inches in area and of various lengths. The galvanized lining of the flume at intervals of 1 foot is ridged or corrugated with $\frac{1}{4}$-inch channels extending up and into the flume. The metal lining on the bottom of the flume is bent down and over the edge of the plank bottom and then bent out and up on the glass side, forming a channel to receive the edge of the glass side. This channel is one-half inch wide and three-quarters inch deep.

THE GLASS SIDE.

One side of the flume is of stock plate glass cut 11 inches wide and 30 inches long. The glass is held in place at the bottom by the channel made by extending the lining of the bottom as described above. The ends of the glass are held in place by double channels made from galvanized iron. These channels are one-half inch in width, three-quarters inch deep, and $10\frac{1}{2}$ inches long. The channels are fastened to the bottom of the flumes by means of screws and are held at the top by strap-iron cross-braces fastened to the wooden side. Melted paraffin is run into the channels at the bottom and end of the glass and a tight joint secured. The end of the flume is closed with a metal gate fastened to the wood of the flume.

SOIL BOXES.

The all-metal boxes as first used were replaced with wooden boxes having a metal lining. The sizes of the boxes were not altered. They are made of 2-inch redwood plank and lined with galvanized iron. The lining extends out and over on the open side of the box. A strip of plate glass held in place by wooden strips is placed on the open side of the box when ready to set in place after packing. The wooden strips are fastened to the box proper by means of eyebolts

having a screw thread and nut for tightening. The joint between the glass and the box is made with a strip of maltoid roofing. The present box gives good satisfaction and is sufficiently rigid to admit of considerable handling without danger of cracking the soil column.

SOIL SAMPLING EQUIPMENT.

The soil samples are taken with a carpenter's bit, the shank of which has been lengthened to 16 inches. The soil samples are placed in 4-ounce glass bottles fitted with aluminum screw caps. They are dried in the usual double-walled water-jacketed oven. The oven used is of local make and of galvanized iron. The inner oven is 12 by 12 inches, fitted with one shelf.

EVAPORATION TANK.

The evaporation tank is made of galvanized iron, and is 18 inches square and 12 inches deep. The tank is set in a wooden box 2 inches larger all around than the tank. This space is filled with soil, thus insulating the tank upon the bottom and sides.

AIR TEMPERATURES.

The air temperatures are taken with a self-recording thermograph. The instrument is set up immediately adjacent to the flumes and is shaded and protected from storm.

ADDITIONAL EQUIPMENT.

A variety of special equipment has been used, and this will be described with the presentation of the data obtained by its use.

RATE AND EXTENT OF MOVEMENT OF SOIL MOISTURE BY CAPILLARITY.

There are so many factors controlling the rate and extent of movement of capillary moisture (4) (11) that it is very difficult to apply the data obtained from one soil to a different soil even of the same type. Without knowing more of the effects of those different factors upon the movement of soil moisture it is not possible to make such comparison and expect accurate quantitative results, even though we have a complete chemical and mechanical analysis of the two soils (8) (15). Within each soil are those influencing factors, such as soluble mineral salts, the organic material, the colloids, and many others, which influence in various and irregular ways the movement of soil moisture by capillarity. Certain other factors, such as the meteorological conditions that may be controlled to a large extent, exert a material influence upon the movement of soil moisture by capillarity.

In so far as the writer knows, there is very little knowledge of the quantitative effect of these different factors upon the movement of soil moisture, general information being limited to the fact that they do influence the movement. There are a few data upon the quantitative effect of temperature (2) and some of the other meteorological factors and also of the soluble salts (3), but they are incomplete and in some instances confusing. In the experiments herein discussed, the evaporation factor has been controlled and taken into account within certain limits, and the results of this work will be discussed later in the report.

In any comparison of the data from one soil with the data obtained from a different soil none of these factors has been taken into account. Chemical and mechanical analyses of the soil can be obtained readily, but with our present knowledge such information would be of no service in making quantitative comparisons. For instance: The colloids influence the movement of capillary moisture in one way, while the organic material, as indicated by the organic carbon, exerts an influence in the opposite direction. There is not sufficient information to indicate in the least to what extent these two factors might compensate, if at all. Other factors tend to retard the movement of the moisture, while others, again, tend to augment it, but to what extent our present information does not indicate.

The experiments herein recorded were run at various times throughout the year and in the open. Some of the soils were tested during the heat of August and others during the cold weather in January. Others of the soils were tested at a time when they encountered periods of almost extreme heat and extreme cold. It is known with reasonable certainty that the rate and extent of movement of soil moisture is greater with temperature above but near the freezing point than at a higher temperature. That a temperature of from 26° to 32° F. has a marked influence upon soil moisture other than the mere fact of freezing will be indicated by data presented later in this report.

In the data herein presented, no corrections are attempted for temperature or other factors unless specifically stated. It must be kept in mind that in the calculations for comparison and in the derivation of formulæ the conclusions reached are applicable only to the soil under consideration and under the same conditions.

MOVEMENT OF MOISTURE IN VERTICAL TUBES FROM FREE WATERS.

The experiments herein recorded differ from other work that has been done in vertical tubes only in that the tubes are larger and the work has been carried to a greater extent (3), (12), (13), (14). These tubes or flumes have also been subjected to variations of tem-

perature corresponding to the daily and monthly variations in temperature of the atmosphere at Riverside.

A feature of the experiments not usually included is a record of the quantity of water required to extend the moisture to various heights.

Below is given a list of the vertical flumes and the soil placed in each.

Flume 19 was filled with decomposed granite from Riverside, Calif.

Flume 43 was filled with heavy soil from Riverside, Calif.

Flume 63 was filled with heavy clay soil from Whittier, Calif.

Flume 80 was filled with gravel soil from Uplands, Calif.

Flume 100 was filled with lava-ash soil from Central Idaho.

Flume 209 was filled with sandy soil from Central Idaho.

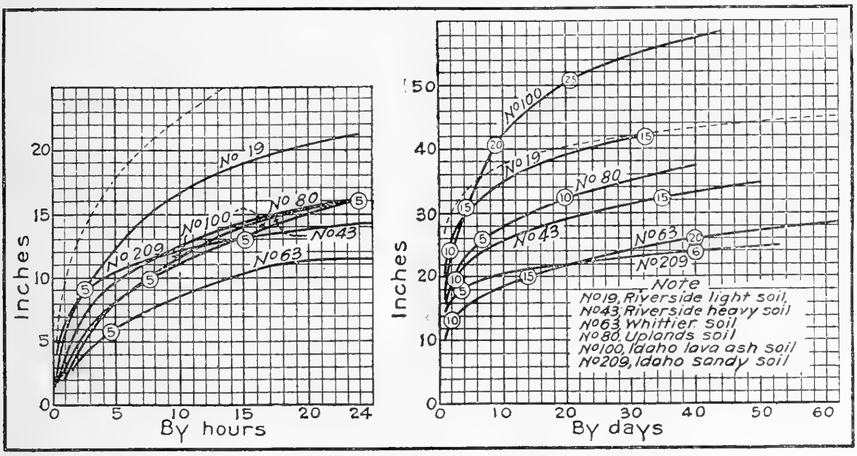

FIG. 2.—Rate of movement of moisture in vertical columns of soil. The numbers within circles indicate the point at which that number of liters of water had been taken up.

The moisture equivalent, in per cent, for these soils is as follows: Riverside, light, 7.9; Riverside, heavy, 14.1; Whittier, 38.3; Uplands, 6.6; Idaho lava-ash, 18.3; and Idaho sand, 4.7.

Figure 2 shows the curves derived from the measurements of the rate of movement of moisture in the flumes and the time of such measurements. The vertical element is the distance measured in inches and the horizontal element is the time in hours or days. The figure to the left shows the rate of movement by hours for the first 24 hours and the figures to the right the movement by days.

The curves are parabolos or closely resemble parabolic curves. A very rapid movement of the moisture occurs for the first few hours of the experiment. After the first few hours there is a rather rapid slowing down of the rate of movement and after about the fifth day the rate of movement is rather uniform, growing slightly slower day by day.

The diagram indicates that the rate of movement in the lighter soils is more rapid for the first few hours and then slows down much quicker than with the heavy soils. The heavier soils maintain a relatively more uniform variation than the lighter soils throughout the experiment.

The heavy Idaho soil is an excellent example of those soils having a high capillary power. It shows a steady extended movement and differs widely from the light Idaho soils, as shown by flume 209.

We find in these soils a variation of nearly 250 per cent in the total distance moved in a period of 30 days. In general, the lighter the soil, the shorter the distance the moisture will move upward in a long period of time.

The unnumbered dotted lines upon both the drawings in figure 2 represent the movement of moisture in vertical tubes of small diameter as found by Loughridge (13). These curves are introduced to show the agreement in results from experiments with small tubes and those from the experiments with flumes at Riverside. The soil used in these small tubes, as indicated by the dotted lines, is an alluvial soil from Gila River Valley.

Table 1 gives, in percentages, that part of the distance moved in 1, 2, 3, 5, 10, and 20 days of the total distance moved in 30 days.

Table 2 gives the same information in hour periods for the first 24 hours.

TABLE 1.—*Daily movement of moisture (distance) in percentage of movement in 30 days.*

Number of days.	Flume.					
	19	43	63	80	100	209
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	51	41	47	46	30	62
2	61	60	57	57	43	71
3	67	66	62	62	51	76
5	74	73	65	70	59	83
10	84	82	76	80	77	89
20	94	93	89	92	92	94
30	100	100	100	100	100	100

TABLE 2.—*Hourly movement of moisture (distance) in percentage of movement in 24 hours.*

Number of hours.	Flume.					
	19	43	63	80	100	209
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	27	15	....	....	14	44
2	39	25	29	38	29	58
3	52	45	....	56	....	69
4	63	57	47	66	55	80
8	72	70	....	71	63	81
12	84	80	83	83	74	90
24	100	100	100	100	100	100

The distance moved in 2 hours, in percentage of the total distance moved in 30 days, or 720 hours, was as follows:

Flume 19, 20 per cent; flume 43, 13 per cent; flume 63, 13 per cent; flume 80, 13 per cent; flume 100, 9 per cent; flume 209, 36 per cent. In 2 hours, or 1/360 of the time, the percentage ranges from 36 in the light Idaho soil to 9 in the heavy Idaho soil, or from about one-tenth to about one-third the total distance.

About the same relative rate of movement of moisture for the first few hours of the experiment is shown by Table 2. In the first 8 hours, or one-third of the 24 hours, the moisture had moved upward more than 70 per cent of the total distance moved in 24 hours, while in the longer period of 30 days it is found that more than 80 per cent of the total distance was covered in one-third of the time.

The above tables and diagram but emphasize and give in some detail the rapid action of capillary moisture when soils are first placed in contact with free water, and show that a large part of the total distance the moisture will move in a month is covered within the first few hours. These results are in accord with those obtained by others. (9)

WATER USED.

The figures within the small circles in figure 2 give, in liters, the total quantity of water removed from the tanks by the soil columns at the end of various periods of time.

At the end of 30 days, flume 63 had taken about 30 per cent more water than had flume 19, and flume 100 had taken up nearly twice as much water as flume 19. Flume 209 used very little water after the first 6 days and a large part of the total water used in the 30 days was used the first day. At the end of 30 days this flume had used only about one-half as much water as flume 19. These figures show, as was to be expected, that the lighter soils require less water per inch than do the heavier soils.

TABLE 3.—*Quantity of water used to move moisture an average distance of 1 inch at the end of different periods of time.*

Number of days.	Flume.					
	19	43	63	80	100	209
	Liters.	*Liters.*	*Liters.*	*Liters.*	*Liters.*	*Liters.*
1	0.422	0.446	0.700	0.250	0.482	0.296
2	.393	.526	.737	.256	.468	.276
3	.392	.506	.726	.323	.506	.265
4	.379	.500	.772	.311	.527	.259
10	.366	.470	.789	.326	.497	.254
20	.364	.484	.810	.317	.488	....
30	.357	.472	.816	.327	.484	.239

Except for the lighter soils of the sandy type, the quantity of water required to move the moisture the first inch is about the same or a little less than to move it the last inch on a basis of 30-day tests. Table 3 brings out the fact that there is much less difference in the quantity of water required per inch for the various heights than is usually supposed. The difference in the percentage of moisture found near the bottom and the percentage found near the top of a vertical soil column containing capillary water raised from a free water surface leads to the natural conclusion that more water per inch is removed for the bottom inches than for the top inches. However, it is observed that in flume 63 the reverse is true, although the percentage of moisture near the bottom of this flume was greater than it was within 4 inches of the top. Under another heading in this report is given at least a partial explanation of this apparent inconsistency. (See p. 56.)

TABLE 4.—*Water removed from tank, by days, in percentage of total removed in 30 days.*

Number of days.	Flume.					
	10	43	63	80	100	200
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	61	47	40	34	30	77
2	67	66	50	43	42	82
3	74	69	55	60	53	84
4	75	72	60	62	60	86
10	86	79	74	77	79	....
15	91	86	87	82	89	....
20	95	91	93	87	92	....
30	100	100	100	100	100	100

Table 4 shows in general the relatively high percentages of water removed from the tanks during the first day or two and the relatively small percentages used after the first three or four days. It is found that in all flumes at the end of the third day, or one-tenth of the 30 days, more than 50 per cent of the water had been used, and by the end of the tenth day three-fourths of the total water used in 30 days had been removed from the tanks. During the last 10 days of the experiment only about 10 per cent of the total water was removed from the tanks.

This table again indicates the longer continued use of the relatively large quantities of water by the heavier soils and the very rapid action of the lighter soils. This is of economic importance in that the loss for an extended time would be much less in proportion for a heavy soil than for a light soil where the loss of water is caused by capillary action alone.

In Table 5 are brought together for comparison the rate of advance of moisture and the quantity of water used, expressed in percentages of the totals for 30 days. (See Tables 1 and 4.)

TABLE 5.—*Percentage of distance moved and percentage of water used by days upon a 30-day basis.*

Number of days.	Flume.											
	19		43		63		80		100		209	
	Distance moved.	Water used.	Distance moved.	Water used.	Distance moved.	Water used.	Distance moved.	Water used.	Distance moved.	Water used.	Distance moved.	Water used.
	Per ct.	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*	*Per ct.*
1	51	61	41	47	47	40	46	34	30	30	62	77
2	61	67	60	66	57	50	57	43	43	42	71	82
3	67	74	66	69	62	55	62	60	51	53	76	84
10	84	86	82	79	76	74	80	77	77	79	89	......
15	....	91	....	86	....	87	....	82	....	89	....	......
20	94	95	93	91	89	93	92	87	92	92	94	......
30	100	100	100	100	100	100	100	100	100	100	100	100

It is observed that in three of the flumes the percentage of the water used at the end of the first day exceeds the percentage of the distance moved; in two of the flumes this condition is reversed and in the other flume the two percentages are identical.

Table 6 shows the percentage of water (by volume) contained in the wet soil at the end of 30 days, and as would be expected, the relatively large quantity of water contained in the heavier soils.

TABLE 6.—*Percentage of water, by volume, contained in the wet soil.*

Flume.	Percentage of water.
19	21.82
43	28.80
63	30.02
80	20.55
100	29.60
209	14.60

Table 7 gives the depth in inches to which the water removed from the tanks at the end of the specified time would cover the surface of the soil column if none of the water so added penetrated the soil. For instance, at the end of the third day 671 cubic inches of water had been removed from tank 19. This quantity of water is sufficient to cover a 10-inch by 10-inch area to a depth of 6.71 inches. In the same way the other figures of the table have been determined. If the area of the flume had been 1 acre instead of 100 square inches there would have been removed from the tank sufficient water to have covered the acre to a depth of 6.71 inches, or, expressed in irrigation terms, there would have been removed from the tank 6.71 acre-inches in the three days.

TABLE 7.—*Depth to which water removed from tanks would cover area of 100 square inches.*

Number of days.	Flume.					
	19	43	63	80	100	209
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1	5.49	4.27	4.88	2.44	4.88	2.59
2	6.10	6.10	6.10	3.05	6.71	2.74
3	6.71	6.45	6.71	4.27	8.54	2.82
4	6.86	6.71	7.32	4.47	9.72	2.89
10	7.78	7.42	9.00	5.49	12.81	....
15	8.24	8.08	10.62	5.86	14.34	....
20	8.62	8.54	11.35	6.24	14.95	....
30	9.06	9.36	12.21	7.17	16.17	3.36
40	9.31	9.70	12.57	7.48	17.39	....
50	....	10.00	13.06	....	18.37	3.86
60	....	....	13.42	....	....	....

Table 7 shows that if a body of water were covered with 40 inches of dry soil of the type in flume 100, there would be removed from it by capillarity in the first 10 days a depth of 12.81 inches of water.

If some means were provided to remove from the end of the wetted soil column in flume 100 after the end of the first day all the water the soil column of this length could transmit, there would be lost from this body of water at least 1.83 acre-inches each day, and in one year the loss would amount to 55.66 acre-feet per acre. This, then, is the transmitting power of the soil column at the end of the first day. That this amount is not lost each day following the first is due to the fact that the soil can not take this amount by capillarity through the distance from the free water. If a calculation were made for this soil to transmit water from the twentieth to the thirtieth day and at the distance from the water to the outer extremity of the moisture at this time, the transmitting power could be 3.17 acre-feet per acre per year or only 6.67 per cent of the transmitting power at the end of the first day. If the same calculation is made for flume 19, it is found that the transmitting power of this soil for the period from the twentieth to the thirtieth day is only about one-third that of flume 100, and about the same relative percentage at the end of the first day.

In flume 19 it is found that the moisture has traveled upward into the flume a total distance of 28.05 inches in three days and that there has been removed from the tank at the end of three days a total of 1,100 cubic centimeters or sufficient to fill the flume to a depth of 6.71 inches. Using these figures, it is found that at the end of the third day there was by volume 23.9 per cent of water in the 28.05 inches of wetted soil. By the same means of calculation Table 8 is computed.

Table 8 indicates that for a period of 30 days the light sandy soils contained a smaller percentage of moisture in the wetted area day by day. The heavier soils, as represented by flumes 43, 63, and

100, maintain a rather uniform percentage of moisture throughout the 30 days. (The distribution of this moisture throughout the column will be given later.) At the end of 62 days flume 63 contained in the wet soil by volume 47 per cent of water, or a little less than at the end of 30 days. At the end of 44 days flume 100 contained by volume 29.8 per cent of water, or about the same percentage contained for the first 30 days.

TABLE 8.—*Percentage, by volume, of water in wetted soil at end of time specified.*

Number of days.	Flume.					
	19	43	63	80	100	209
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	25.7	27.2	42.6	15.3	30.0	18.0
2	24.0	32.2	45.0	15.6	28.6	16.9
3	23.9	31.0	44.3	19.9	30.6	16.1
4	23.1	30.5	....	19.3	32.0	15.8
10	22.3	28.0	48.2	19.9	30.3	....
20	22.0	29.4	51.7	19.4	29.0	....
30	21.8	28.8	50.0	20.6	29.6	14.5

Table 8 would indicate further that capillary action must take place much slower in heavy soils than in light soils, due to the relatively higher percentage of moisture in the heavy soils at all points in the column. It takes a higher relative percentage of moisture in the heavy soils to permit the advance of moisture from a damp to a dry soil by capillary action. The lighter soils will contain a relatively smaller percentage of moisture in the very extremity of the wetted area as it advances than will the heavier soils.

DISTRIBUTION OF SOIL MOISTURE IN VERTICAL SOIL COLUMNS.

The distribution of moisture in a vertical column of soil, the lower end of which is in contact with a body of water (9), has received considerable attention in these experiments. The study has included the distribution for the various lengths of time up to and including 40 days. In Table 9 is given the distribution in two vertical columns for periods of 30 days, or after the column has been in contact with the water for a period of 30 days. Flume 43 is Riverside soil No. 1, and flume 63 is the Whittier soil. Flume 63 was closed to evaporation, while flume 43 was open upon one side, and the soil is held in place by brass-wire gauze.

TABLE 9.—*Distribution of moisture in vertical soil columns.*

Distance above water level (inches).	Riverside soil No. 1: Flume 43.	Whittier soil: Flume 63.
	Per cent.	*Per cent.*
1	17.40	46.74
3	17.40	45.53
6	20.44	40.25
9	18.84	40.70
12	12.67	40.84
15	....	38.11
18	12.65	36.49
21	....	34.75
24	12.44	30.82
28	....	24.59
30	10.15	....
31	....	5.59
36	6.36	4.60

The figures show that the decrease in the percentage of moisture from the water surface to the upper extremity of the wetted area is not uniform. In flume 43, the greatest percentage of moisture is

found at a height of 6 inches above the water. In flume 63 there is a greater percentage of moisture in the twelfth inch than in either the sixth or the ninth inches. In both flumes there is a decrease in the percentage of moisture with height above the twelfth inch. In flume 43 there is a much more constant and uniform percentage of moisture from the twelfth inch to near the top of the wet area than there is in flume 63. In both flumes, the moisture content breaks very abruptly near the upper end of the wet soil and indicates the relatively high percentage of moisture necessary to allow the moisture to move from the wet to the dry soil.

Other and very much more numerous data show the irregularity of moisture distribution in vertical columns even though every precaution is taken to have the soil uniform in texture and in density. A superficial study of these data would indicate that a formula that would give the distribution of moisture in vertical soil columns for a period of 30 days would be more complicated than the formula for the movement of moisture. An analysis of the above statement would indicate that the percentage of moisture which will permit the advance of moisture from the wet to the dry soil is variable, even for uniform temperatures, etc.

The data for flumes 43 and 63 given above, and numerous other data show a distribution of moisture contrary to general supposition.

That there is a lack of uniformity in the distribution of moisture in vertical soil columns has been observed by others (6), (13).

THE MOVEMENT OF MOISTURE IN HORIZONTAL FLUMES.

The horizontal capillary movement of moisture within the soil and from a body of free water has not been studied before to any great extent (12).

Much of what has been said of the vertical flumes is applicable to the horizontal flumes. The chief difference is rather one of degree.

At the present time there will be discussed only the horizontal flumes open on top to evaporation.

The number of flumes and the soil contained in each is given in Table 10.

TABLE 10.—*Soil in horizontal flumes.*

Number of flume.	Description.
20	Decomposed granite soil from Riverside, Calif.
31	Heavy decomposed granite soil from Riverside, Calif.
50	Heavy clay loam from Whittier, Calif.
70	Sand and gravel wash from Uplands, Calif.
90	Heavy lava ash from Idaho.
200	Light sand soil from Idaho.

Figure 3 shows the curves derived from the measurement of the movement of moisture in the horizontal flumes and the time

of such measurements. The vertical element is the distance measured from the surface of the water in the tank and the horizontal element is the time in days.

The resulting curves for all these soils have the parabolic form. Very rapid movement of the moistures occurs for the first few days, after which the rate of movement is more uniform, but it gradually decreases with the lapse of time. It is observed from the figure that the rate of movement of moisture in the heavier soils, as typified by the Whittier soil, subsides much more rapidly than does the movement in the sandier soils.

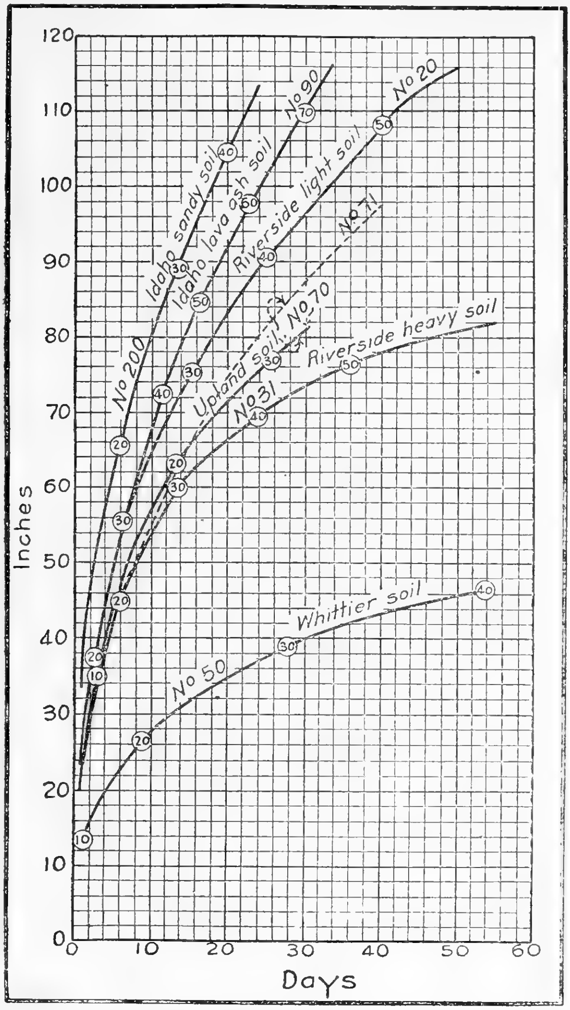

Fig. 3.—Rate of movement of moisture in horizontal open flumes. Figures in circles indicate points at which that number of liters of water had been taken up. The dotted line for flume No. 71 (covered) is for comparison with flume No. 70 (open).

The extent of movement of moisture in these soils is, with the exception of Idaho lava soil, in inverse order to their moisture equivalents. That is, the Idaho soil (sandy) with the lowest moisture equivalent showed the greatest movement of moisture, while the Whittier soil with the greatest moisture equivalent showed the least movement of moisture. The Idaho lava soil in the horizontal flume as in the vertical flume showed a greater movement of moisture than the moisture equivalent would indicate.

The figures within the small circles give in liters the quantity of water removed from the tanks by the soil columns at the ends of various periods of time.

Table 11 gives the percentages of water used in 1, 3, 5, 10, 15, and 20 days of the total quantity used in 30 days.

TABLE 11.—*Water removed from tanks by days expressed in percentages of amount removed in 30 days.*

Number of days.	Flume.				
	20	31	50	70	90
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	17	22	26	18	17
3	30	36	42	30	29
5	38	42	51	36	37
10	53	58	67	52	53
15	67	70	78	64	67
20	81	81	86	79	81
30	100	100	100	100	100

Table 11 shows the relatively great use of water the first few days of the experiment. In all cases more than one-half the total quantity of water used in 30 days was used the first 10 days or one-third of the time. From 17 to 26 per cent of the total quantity used in 30 days was used the first day and in two-thirds of the 30 days more than 80 per cent of the water was used. The lighter the soil the smaller the relative percentage of water used the first few days, and the heavier the soil the greater the relative use of water during the first few days. However, the lighter the soil the greater the total quantity that will be used in long periods of time. This is the opposite of the conditions with the vertical flumes and is worthy of note. The heavier the soil the less extended will be the wetted area with the lapse of time, which condition is as would be expected. That is, a sandy soil or a light soil will "sub" much farther in a horizontal direction than a heavy soil. The results indicate also that a heavy soil loses more water through evaporation when the soil is 10 or more inches deep than a sandy soil. This can be accounted for from the fact that the capillarity of the sandy soil is not sufficiently great to keep the surface wetted to the optimum capillary capacity for evaporation. It shows also the influence of gravity even in these horizontal flumes 10 inches in depth. Table 12 gives the percentage of the total distance moved and the percentage of the total water used in 30 days for different periods of time.

TABLE 12.—*Distance moved and water used, expressed in percentages of the total for 30 days.*

Number of days.	Flume.									
	20		31		50		70		90	
	Water.	Distance.	Water.	Distance.	Water.	Distance.	Water.	Distance.	Water.	Distance.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	17	....	22	27	26	28	18	29	17	21
3	30	33	36	46	42	45	30	....	29	34
5	38	42	42	56	51	....	36	52	37	44
10	53	64	58	73	67	69	52	70	53	62
15	67	69	70	84	78	80	64	81	67	74
20	81	82	81	91	86	87	79	88	81	84
30	100	100	100	100	100	100	100	100	100	100

The tables show what was to be expected, that relatively more water was required to advance the wetted area in the flume 1 inch near the end of the experiment than at the commencement of the experiment. This fact may be partially or wholly due to the loss of water by evaporation. However, from data secured with the vertical flumes it may be partially due to changes in the distribution of moisture through the length of the flumes.

Table 13 gives the average quantity of water, in cubic centimeters, required to advance the moisture in the flume 1 inch for different periods of time.

TABLE 13.—*Average use of water to advance the moisture 1 inch for different periods of time.*

Number of days.	Flume.					
	20	31	50	70	90	200
	c. c.	*c. c.*	*c. c.*	*c. c.*	*c. c.*	*c. c.*
1	....	500	711	259	524	300
3	380	474	728	....	532	290
5	384	461	....	288	537	305
10	400	488	764	300	545	....
15	413	501	775	320	577	345
20	422	552	778	366	617	380
30	425	616	789	408	637	....

Since these flumes are open to evaporation, more water is required to advance the moisture an inch as the distance from the tank increases. In some instances the amount of moisture required to advance the wetted area 1 inch at the end of 30 days is nearly double that required the first few days. In the heavier types of soils, as represented by flume 50, a more constant quantity is required during each of the 30 days than for the lighter soils as represented by flume 70. Table 13 indicates also that less water is required to advance

the moisture an inch in light soils than in heavy soils. In flume 31 more moisture was required per inch of advance during the first few days than during the fifth day, but after the fifth day there was a gradual increase in the moisture required. This same condition was found in flume 200. It is probable that this results from the fact that the moisture percentage changes to a very much greater extent near the tank end of the flume than it does toward the other end, and especially is this true the first few days. It is also noted from the results of the vertical flumes that for a distance of 14 inches above the surface of the water the moisture moves rather slowly upward. It is probable, therefore, that during a period along about the fifth day there is not sufficient moisture near the top of the flume to permit a maximum evaporation. After that time evaporation takes place more rapidly and hence the increase in water consumed. Another fact that will be brought out in the distribution of the soil moisture in these flumes is the gradual increase in the percentage of moisture throughout the wetted area of the flume from day to day, this constantly increasing percentage continuing until very near the point of capillary saturation.

In a review of Table 13 it is found that the order of the water requirements of these flumes at the end of the twentieth day, beginning at the one requiring the least water, is flume 70, 200, 20, 31, 90, and 50. Comparing this order with the order of the moisture equivalents of these soils, and beginning with the least moisture equivalent, we find the order just the same as above, except that flumes 70 and 200 are reversed. This interchange of place is probably accounted for by the fact that flume 200 would permit of more evaporation per square inch than would flume 70.

From the data in Table 13 it is possible to calculate for the horizontal flumes the quantity of water removed during any period of time, in cubic inches. Assuming the same rate of use in nature as in the flumes, the use of water by the soil in place can be calculated in acre-inches. In preparing Table 14 such assumptions were made.

TABLE 14.—*Loss of water from tanks in different periods of time. (Depth expressed in inches on an area of 100 square inches.*

Number of days.	Flume.					
	20	31	50	70	90	200
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1	4.58	6.10	4.88	3.67	7.32	6.10
3	7.93	9.76	7.93	6.10	12.21	9.15
5	10.07	11.59	10.76	7.34	15.87	11.59
10	14.34	15.87	12.81	10.37	22.58	15.25
15	18.00	18.22	14.95	12.82	28.68	19.53
20	21.82	22.27	16.48	15.87	34.78	24.40
30	26.85	27.46	19.12	20.14	42.72	....

Table 14 is interesting from the fact that at the end of the first few days the use of water by the flumes containing the lighter soils is greater than for the flumes containing the heavier soils. The use of water by flume 50, containing the Whittier soil, is, after the first few days, considerably slower than that by flume 200, containing the light sandy Idaho soil. This fact is of importance and confirms the observations in nature of the excessive loss by capillarity in conveying channels constructed through sandy soils. This table, in connection with figure 3, indicates the extensive and long-continued capillary action in a horizontal direction in the lighter soils.

DISTRIBUTION OF MOISTURE IN HORIZONTAL FLUMES.

In considering the distribution of moisture in horizontal flumes open on top to evaporation, it is difficult to obtain uniform comparable results. This is due to the fact that the flumes were exposed to the natural changes of meteorological condition and many of them were in operation during the extremes of temperature. Another fact that is of primary importance is the effect of temperature upon the vertical distribution of moisture within the flume. With temperatures near the freezing point and with the soil containing about its maximum capillary capacity of moisture, a distribution of moisture is found in the soil differing materially from the distribution in the same soil with higher temperatures. It is not thought, therefore, of value in presenting a few data to attempt any specific calculations, but only general comments are made.

In Table 15 the first column gives the date on which the sample was taken; the second column gives the distance along the top of the flume, measured from the intersection of the top line of the flume and a vertical extension of the inside of the vertical part of the wick. This point is 19¼ inches above the water surface, measured along the upper side of the wick. The third column gives percentages of moisture at the various points for the top 5 inches of the flume, and the fourth column for the bottom 5 inches of the flume. The fifth column gives the average percentages of moisture at the various points.

Taking the average percentages of moisture in flume 31 at the same point and on different dates, it is found that the percentage of moisture gradually increases until the warmer weather in June. After that time there may be a slight decrease in percentages of moisture at the different points. Taking a sample at the 9-inch point, we find this to be true and that the percentage of moisture on June 10 had decreased about 2.2 per cent from what it was on May 23. Comparing the percentage of moistures for the top 5 inches of soil at the 9-inch point, we find that throughout the entire time there was a gradual increase in the percentage of moisture, while the bottom 5 increased in moisture content until April and then decreased.

TABLE 15.—*Distribution of moisture in horizontal flumes.*

FLUME 20.

Date.	Distance.	Top 5 inches.	Bottom 5 inches.	Average.
	Inches.	*Per cent.*	*Per cent.*	*Per cent.*
Apr. 18..	3	25.72	23.04	24.38
	9	20.21	21.45	20.85
	21	19.80	21.82	20.81
	45	17.00	19.44	18.22
	69	15.74	17.66	16.70
	81	12.00	16.47	14.24
	93	13.34	15.03	14.18
	105	11.52	13.21	12.36
	111	10.30	10.78	10.54
	117	8.36	6.76	7.56

FLUME 31.

Date.	Distance.	Top 5 inches.	Bottom 5 inches.	Average.
Apr. 20..	9	21.29	22.96	22.12
	15	20.42	21.66	21.04
	21	18.99	20.00	19.50
Apr. 29..	9	23.02	25.49	23.75
	15	23.02	24.52	22.39
	27	21.82	22.96	22.39
	33	18.98	21.84	20.41
May 23..	9	23.66	25.07	24.36
	33	20.39	22.76	21.57
	51	18.45	20.18	19.31
	59	16.43	17.76	17.09
June 10 .	9	23.72	21.98	22.85
	22	22.55	23.65	23.10
	34	19.77	22.74	21.25
	52	18.35	20.64	19.50
	64	13.81	17.88	15.85

FLUME 50.

Date.	Distance.	Top 5 inches.	Bottom 5 inches.	Average.
Sept. 21.	3	43.31	45.86	44.58
	12	44.50	42.52	43.61
	24	39.16	41.82	40.49
	30	38.92	39.94	39.43
	33	35.65	37.01	36.33

FLUME 70.

Date.	Distance.	Top 5 inches.	Bottom 5 inches.	Average.
	Inches.	*Per cent*	*Per cent.*	*Per cent.*
Oct. 14..	3	13.80	14.60	14.20
	30	4.59	9.62	7.10

FLUME 90.

Date.	Distance.	Top 5 inches.	Bottom 5 inches.	Average.
Jan. 29..	½	28.80	28.81	28.80
	18	26.37	26.66	26.52
	42	19.30	20.07	19.69
Feb. 29..	½	30.53	29.15	29.84
	18	28.44	27.87	28.15
	42	25.44	25.04	25.24
	72	18.81	19.75	19.28
Feb. 22..	½	32.30	29.83	31.07
	9	30.22	27.49	28.85
	18	28.35	26.17	27.21
	30	26.76	26.05	26.40
	42	25.86	25.27	25.57
	54	25.35	25.58	25.47
	72	17.65	23.33	20.49
	84	22.35	22.80	22.57
	96	18.53	19.87	19.20
Mar. 5...	½	31.53	29.52	30.52
	18	27.44	26.30	26.87
	42	26.33	25.66	25.99
	72	23.37	23.67	23.52
Mar. 10..	37½	26.50	26.00	26.25

FLUME 200.

Date.	Distance.	Top 5 inches.	Bottom 5 inches.	Average.
Apr. 7...	3	11.92	16.28	14.10
	4	12.50	18.25	15.37
	28	10.37	11.95	11.34
	46	14.61	16.71	15.66
	64	9.59	13.00	11.30
	End.	4.43	5.02	4.72

In flume 90 the same conditions are found as in flume 31, except that during the months of January and February there is an apparent discrepancy in the percentages of moisture in the bottom 5 inches and the top 5 inches of soil. This apparent discrepancy is probably the result of temperatures below the freezing point and will be considered in a subsequent part of this report in connection with other similar analyses.

All of the flumes show a gradual decrease in the percentage of moisture from the tank end of the flume to the outward extremity of the wetted area. In flume 20, the average percentage of moisture decreases at the rate of approximately 1.75 per cent for each linear foot between the third and eleventh feet. In flume 50 the rate of decrease is about 2.2 per cent per linear foot. The rate of decrease varies in these flumes, as would be expected not only from the different meteorological conditions when the experiments were run, but also from the character of the soil.

FLUMES INCLINED DOWNWARD FROM THE HORIZONTAL.

The flumes in which it was intended that gravity should assist the capillary movement of moisture were inclined downward at various angles from the horizontal. In all the flumes inclined in this way the movement of the moisture and the amount of water used were greater than for the horizontal flumes or the flumes inclined upward from the horizontal. The extent to which water would move in the inclined flumes where the inclination downward was 10 degrees or more was, in most cases, beyond the limits of the equipment used. Most of the experiments were carried to such an extent as to warrant certain conclusions. The extent of this movement in the open flumes appears to be limited not by the friction factors, but by the power of the wick to supply moisture in sufficient quantity to take care of the evaporation from the flume. That is, were evaporation eliminated, the extent of movement in the flumes inclined downward at angles greater than 30 degrees, except for the very heavy soils, would be far beyond experimental limits. In the case of the very heavy soils, as typified by the Whittier type, there were indications that in the less steeply inclined flumes friction played its part here as well as in the horizontal flumes.

In distribution of moisture there are found some differences between these flumes and either the vertical or the horizontal; and, as will be shown later free water was developed in the flumes inclined downward.

SOILS USED.

Table 16 gives the numbers of the flumes and the soil contained in each:

TABLE 16.—*Soils in flumes inclined downward.*

Number of flume.	Description.
4	Decomposed granite soil from Riverside, Calif.
34	Decomposed granite and clay from Riverside, Calif.
54	Heavy clay soil from Whittier, Calif.
74	Sand and gravel soil from Uplands, Calif.
94	Lava ash from Idaho.
204	Sandy soil from Idaho.

Figure 4 gives the dates and measurements for the movement of moisture in flumes inclined at an angle of 30 degrees and open on top to evaporation. The horizontal element is the time and the vertical element the distance in inches.

A comparison of figure 4 with figure 2 shows very strikingly the part gravity plays in capillarity. It shows to what extent gravity aids or retards the movement of soil moisture by capillarity. Another striking feature is the comparative uniformity of the rate of movement of the moisture after the first three or four days. While there is a general slowing down of the rate at which moisture advances from day to day, it is so much less marked in these flumes than in the flumes discussed in previous sections as to be of comparatively little moment.

It is observed that after the first day or two the type of soil used in the flumes is of greater importance in limiting the extent of the movement of the moisture. The more open and porous the soil, the more rapid and extended the movement of the moisture. For instance, in the sandy Idaho soil of flume 204, the moisture advanced as far in one day as it would in the heavy Riverside soil in five and one-half days and 50 per cent farther in the first day than it would in the heavy Whittier soil in 30 days. In flume 204 the only limit to the extent of the movement of moisture was the ability of the wick to furnish the moisture. However, the porosity of the soil is not the only factor, but the transporting power of the soil itself is of prime importance. For instance, comparing flume 34 (heavy Riverside) with flume 74 (Upland), flume 34 has the greater rate of movement of moisture at all times within the limits of the experiment, and yet the soil of flume 74 has the greater porosity. The difference in the rate of movement in these two soils appears to be due to the difference in the capillary power of the wick to transmit the water from the tanks to the flumes proper. Had there been less vertical lift from the tank to the flume by the wick, flume 74 would undoubtedly have shown the greater rate of moisture movement. The effect of porosity is well illustrated in flumes 74 and 94. The soil in flume 94 has the greater porosity, and while the rate of movement of the moisture is less in this flume for the first week, it has the greater rate of movement thereafter. Again, comparing flumes 4 and 34, the soil in flume 4 has the greater porosity, but the soil in flume 34 the greater capillary power, and after the first two weeks the rate of movement of moisture in flume 34 is greater.

In table 17 is given the extent of movement of moisture as shown in figure 4, in percentages of the extent of movement in flume 34.

That is, in flume 34 the moisture had moved the first day 26 inches, or 100 per cent. In flume 4 the moisture had moved the first day 28.85 inches, or, as compared with the movement of moisture in flume 34, 111 per cent, while in flume 54 the moisture had moved 10.7 inches, or, based on the movement in flume 34, 41 per cent. Flume 34 maintained a relatively higher rate of movement of moisture than

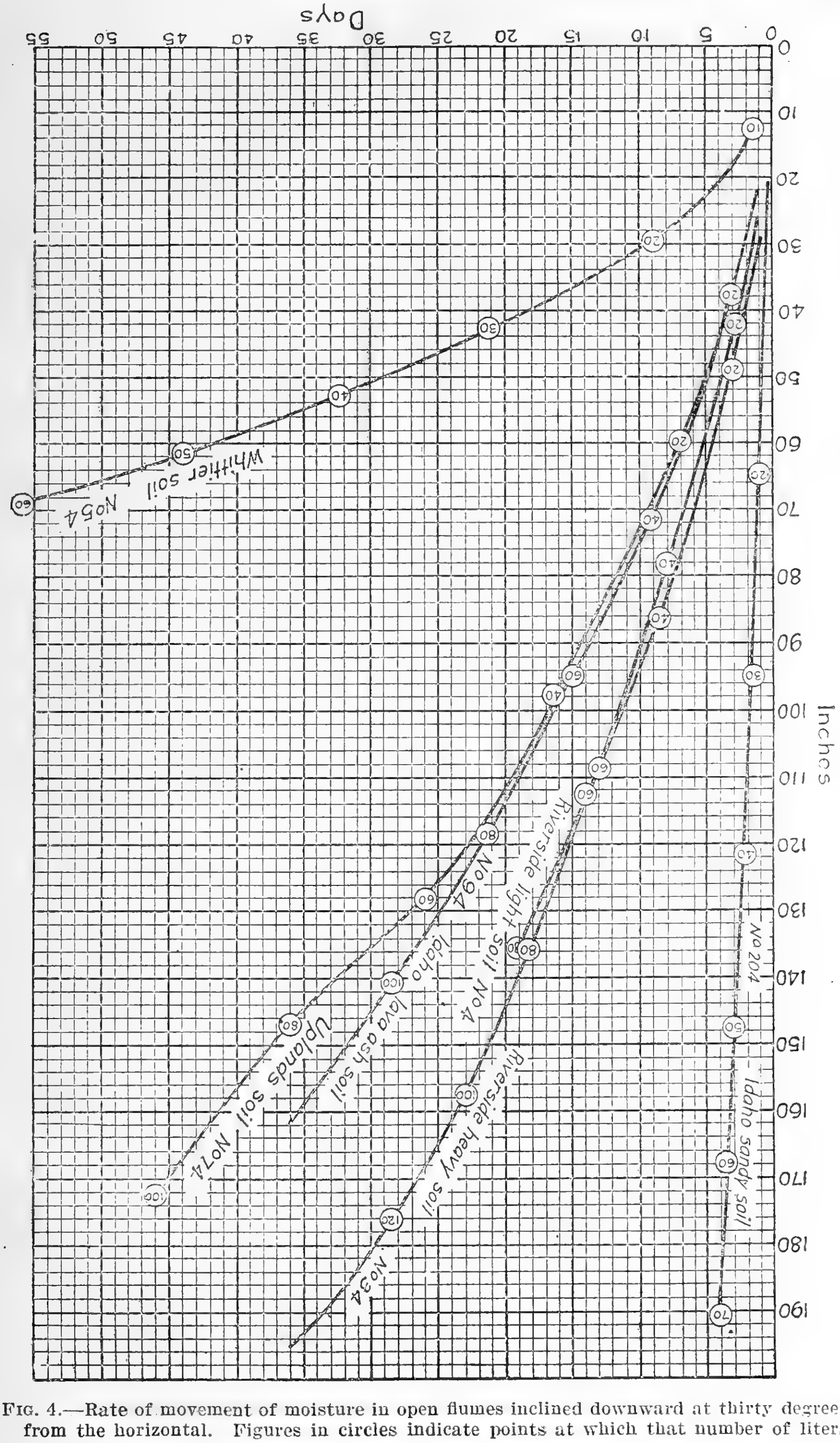

FIG. 4.—Rate of movement of moisture in open flumes inclined downward at thirty degrees from the horizontal. Figures in circles indicate points at which that number of liters of water had been taken up.

any other flumes, although flume 94 maintained nearly the same rate after the first day. In view of the fact that these flumes were operated at different seasons of the year, it is not possible to say to what extent the variable meteorological conditions might have influenced the results.

TABLE 17.—*Comparative movement of moisture, in percentages of movement in flume 34.*

Number of days.	Flume.				
	4	34	54	74	94
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	111	100	41	85	82
3	111	100	42	87	85
5	108	100	39	87	87
10	102	100	34	79	83
15	99	100	31	78	78
20	....	100	29	78	78
30	....	100	27	75	89

In Table 18 there is shown for each flume the percentage of the total distance moved in 30 days that had been moved in 1, 3, 5, 10, 15, and 20 days.

Table 18 shows in another way what has been previously stated. The heavier soil and less porous soils show a relatively greater percentage of movement of moisture the first day or two and a relatively slower rate of movement the last few days. The lighter and more porous soils show the more uniform and more extended movement of the moisture. It is found that in all the flumes, in 5 days, or one-sixth of the 30 days, more than one-third of the total 30-day distance was traveled; in 10 days, or one-third of the time, more than one-half the distance has been traveled, and in 20 days, or two-thirds of the time, more than four-fifths the distance has been covered.

In the discussion previously given of these flumes only the 30-day limit of time was used. However, in figure 4 the curve for flume 54, the heavy Whittier soil, shows that after 30 days the rate of movement of the moisture continues to grow less and less every day, although there is considerable uniformity in the rate of decrease of movement. The figures would indicate that the movement of moisture would reach a considerably greater distance than that shown upon the figure. It is seen that in flume 74 (Upland soil) after 47 days the rate of movement of the moisture is not much less than it was at 30 days, and the evidence is that the moisture would continue to move in this flume rather indefinitely; especially would this be true were evaporation prevented.

TABLE 18.—*Movement of moisture by days, in percentages of total movement in 30 days.*

Number of days.	Flume.			
	34	54	74	94
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
1	14	22	16	15
3	28	37	29	26
5	32	46	37	35
10	50	62	53	52
15	65	74	68	65
20	79	85	82	80
30	100	100	100	100

WATER USED.

The figures in the small circles show in liters the water used by these flumes. The water used by flumes inclined downward is, like the movement of the moisture, greater than for the horizontal or vertical flumes. A striking feature is the rather uniform use of a comparatively constant quantity of water after the second or third day. The rate of use is more constant and uniform than for the vertical or horizontal flumes. Flume 34 had used on the tenth day about 4 liters of water; on the twentieth day about 8 liters; on the thirtieth day about 11.5 liters; and on the fortieth day about 14 liters. In flume 54 with the heavy Whittier soil an even greater uniformity is observed. In this flume there was used approximately the same quantity of water every day after the sixth day up to the fifty-seventh day, or at the end of the experiment. The same uniformity is found, in fact, in nearly all of the other flumes. One fact worth special notice is that the use of water by the flume as represented by the loss of water from the tanks is that evaporation does not appear to have varied the use to any extent. This is true though the same flume was exposed to almost all the different and variable weather conditions found at Riverside. To show the relative uniformity in the rate of use of water by some of these flumes Table 19 has been prepared.

TABLE 19.—*Water used, by days, in percentages of total use in 30 days.*

Number of days.	Flume.			
	24	54	74	94
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
1	9	22	10	11
3	18	35	19	20
5	23	43	25	28
10	39	57	41	43
15	54	68	55	57
20	71?	78	68	70
30	100	100	100	100
40	121	127	129	....
50	....	149	....	....

Table 19 shows that the heavier soils use relatively more water at the commencement than near the end of the experiment. It shows, also, a more uniform use by the heavier soils. It shows, for instance, that the soil in flume 54 had used relatively more than twice as much water as any other flume at the end of the first day, while on the fifteenth day it had used relatively only about one-fifth more than the others. Table 20 shows the amount of water required at different periods of time to advance the moisture in the flumes an average distance of 1 inch. For instance, on the third day, flume 24 had used 18 liters of water and the moisture had advanced 44.15 inches, or an average of 479 cubic centimeters of water was required per inch.

A comparison of the figures in Table 20 with the moisture equivalents of the soils appears to show no close relation. However, in a general way the greater the moisture equivalent the greater the quantity of water required to advance the moisture 1 inch. It is ob-

served in nearly all of the flumes that less water is required per inch about the third day than at any other time. In all cases, however, more water was required per inch at the end than was required at the beginning of the experiment. It is observed that for soils of the heavier type represented in flume 54, for some time after the commencement of the experiment less water is required per inch than for the following day, but after about the thirtieth day there is a very rapid increase of the water requirements. It is probable that there is some concentration of moisture at the top of the vertical lift before the moisture changes direction to the inclined part of the flume and that this moisture is partially drawn upon to advance the moisture in the inclined part of the flume. After a few days this surplus supply, if such it may be called, is exhausted and then the moisture to advance the wetted area in the flume can be derived only from the supply in the tank. It must be kept in mind also that with the lapse of time a greater wetted area is exposed to evaporation, and this in itself would account for some additional water requirement per inch. In some cases the water requirement per inch at the end of the fortieth day was about double the requirement the first day, but in the heavier soils this is not so pronounced.

TABLE 20.—*Water used to advance moisture 1 inch at different times, in cubic centimeters.*

Number of days.	Flume.					
	4	34	54	74	94	204
	c. c.	*c. c.*	*c. c.*	*c. c.*	*c. c.*	*c. c.*
1	319	385	743	290	566	311
3	346	447	707	338	562	360
5	425	498	700	336	571	
10	450	533	677	364	597	
15	545	569	680	411	634	
20		607	697	419	647	
30		684	735	507	724	
40			806	567		
50			846			
57			884			

FLUMES INCLINED UPWARD FROM THE HORIZONTAL AT AN ANGLE OF 15°.

To throw some light upon the effect of a relatively small inclination of the flumes upward from the horizontal, the data will be given and discussed for the flumes inclined upward at an angle of 15° and open on top to evaporation. The flumes are the same in every respect as the others, except the angle of inclination. In these flumes there is a vertical lift of 4 inches before a change is made in the direction of the flumes.

They show a much less movement of the moisture and a much less use of water than the horizontal flumes, but a more extended movement of the moisture and greater use of water than the vertical flumes.

SOILS USED.

Table 21 gives a list of the flumes inclined upward at an angle of 15° and soils contained in each.

TABLE 21.—*Soils in flumes inclined upward at an angle of 15°.*

Number of flume.	Description.
39	Decomposed granite with clay from Riverside, Calif.
58	Heavy clay soil from Whittier, Calif.
76	Sand and gravel soil from Upland, Calif.
96	Lava ash from Idaho.
206	Sandy soil from Idaho.

MOVEMENT OF MOISTURE.

Figure 5 gives the distance the moisture had moved in the flumes at the end of the time indicated. The horizontal element is the time in days and the vertical element is the distance in inches.

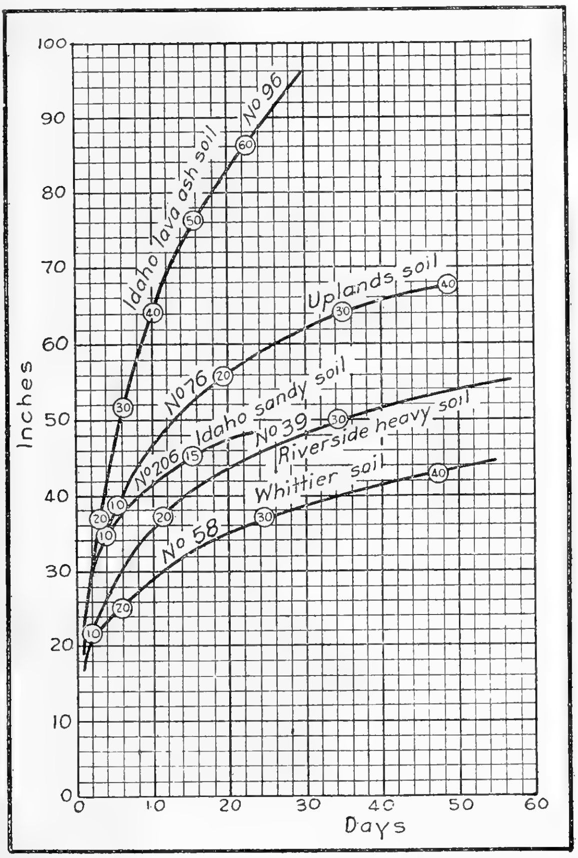

FIG. 5.—Rate of movement of moisture in open flumes inclined fifteen degrees upward from the horizontal. Figures in circles indicate the points at which that number of liters of water had been taken up.

From figure 5 it is seen that the curves for the movement of moisture have the same parabolic form as the curves in the preceding figures. A comparison of these curves with those for the vertical and horizontal flumes shows the importance of gravity in the rate and extent of movement of moisture by capillarity.

The curves show that the rate of movement of moisture is rather more uniform over an extended period than in the vertical flumes. After the first two or three days there is a gradual slowing down of the rate of movement from day to day. Where the experiment is carried on for 50 days or more it is observed that the rate of movement is very slow at that time.

Table 22.—*Extent of moisture movement in flumes at various times.*

Number of days.	Flume.			
	39	58	76	96
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
1	34	30	30	21
3	51	53	53	37
5	59	59	61	48
10	74	75	75	66
15	83	84	84	78
20	90	91	90	86
30	100	100	100	100
40	106	108	106	....
50	112	....	109	....

Table 22 gives the extent of the movement of the moisture at various times, in percentages of the movement in 30 days.

It is observed from Table 22 that the relative rate of movement in the first three flumes day by day was about the same. In flume 96, however, the rate of movement of the moisture was relatively not so great during the forepart of the experiment, but that a more uniform rate of movement was maintained throughout. In the first three flumes more than one-half of the total 30-day distance had been traveled in three days, or one-tenth of the time, and in two-thirds of the time more than nine-tenths of the 30-day distance had been traveled. In flume 96 on the third day only about one-third of the distance had been traveled, and it was not until about the sixth day that one-half of the distance had been traveled.

Table 23.—*Relative movement of moisture, by percentage of movement, in flume 96.*

Number of days.	Flume.				
	39	58	76	96	206
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	80	56	90	100	117
3	69	56	91	100	90
5	62	50	82	100	80
10	57	46	73	100	66
15	54	44	70	100	60
20	53	43	68	100	57
30	50	40	65	100	....

From Table 23 it is found that on the thirtieth day the moisture in flume 58 had moved but 40 per cent as far as in flume 96, while in flume 39 the moisture had moved one-half as far as in flume 96.

All of these flumes when compared with flume 96 show a lesser relative movement during the latter part of the experiment than during the forepart of the experiment. This table shows also that the heavy soil as represented in flume 58 has a much less rapid rate of movement during the forepart of the experiment, but that the

rate of movement as compared with flumes 39 and 76 is more uniform. The figures for flume 206 show the rapid decrease of rate of movement of the moisture from day to day.

WATER USED.

The amount of water used in the flumes inclined upward is greater than for the vertical flumes and less than for the horizontal flumes. The total quantity of water used by the flumes inclined at an angle of 15° upward from the horizontal is given in liters in figure 5 in the small circles. Table 24 gives the total quantity of water, in liters, used by the different flumes at the end of different periods of time. The same information is given in Table 25, in percentages based upon the quantity of water used by each flume at the end of the thirtieth day.

TABLE 24.—*Water used by flumes at different periods of time.*

Number of days.	Flume.				
	39	58	76	96	206
	Liters.	*Liters.*	*Liters.*	*Liters.*	*Liters.*
1	7.5	10.5	5.0	11	7.0
3	13.0	15.0	8.0	20	9.0
5	15.5	19.0	10.0	27	10.5
10	19.0	23.0	14.0	39	13.5
15	22.0	25.5	17.0	48	14.75
20	24.5	28.0	20.5	56	15.75
30	27.5	32.5	26.25	65	....
40	31.25	36.75	33.0	....	....
50	35.0	41.0	40.0	....	....

This table shows that the heavier soils as represented in flumes 39 and 58 use relatively more water during the first few days of the experiment than do the lighter soils. In the heavier soil about the fourth day 50 per cent of the total quantity of water used in 30 days had been used, while for the lighter soils there had been used on the fourth day only about one-third the quantity used in 30 days.

TABLE 25.—*Water used, by days, in percentages of total used in 30 days.*

Number of days.	Flume.			
	39	58	76	96
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*
1	27	32	19	17
3	47	41	31	31
5	57	59	38	41
10	69	71	53	60
15	80	78	64	74
20	90	86	78	86
30	100	100	100	100
40	114	113	125	....
50	124	126	152	....

Table 26 gives the average quantity of water removed from the tanks at different periods of time to advance the moisture in the flumes an average distance of 1 inch. That is, in flume 39 at the end of the fifth day there had been removed from the tank 15.5 liters of water and the moisture had advanced in the flume a total distance of 28.55 inches, or there had been used an average of 543 cubic centimeters of water for each inch the moisture had advanced.

Table 26 shows that in the lighter soils the quantity of water used near the beginning of the experiment was very much less than the quantity of water used during the last part of the experiment. In

flume 76 at the end of the fiftieth day there was used twice as much water per inch as for the first day. In flume 39 there is shown after the third day somewhat of an increase in the use of water from day to day, but it is much less marked than in any of the other flumes. In flume 96 the use of water on the thirtieth day is about 25 per cent in excess of the use on the first day. The increase in the quantity of moisture required per inch with the lapse of time is probably due largely to the effect of evaporation. In flume 58 the distribution of moisture was so uniform as compared with the other flumes that the quantity of water in the flume per inch throughout its length is almost the same, with the exception of the upper few inches. In the other flumes there is a marked decrease in the percentage of moisture from near the tank to the outer extremity of the flume. The relation of the figures in this table to each other corresponds very closely with the relation of the moisture equivalents for the soils represented.

TABLE 26.—*Water used per inch of advance.*

Number of days.	Flume.				
	39	58	76	96	206
	c. c.	*c. c.*	*c. c.*	*c. c.*	*c. c.*
1	406	816	272	541	297
3	530	835	245	558	278
5	543	826	266	589	290
10	531	786	302	617	325
15	556	782	327	644	301
20	573	792	366	679	348
30	548	840	423	676	----------
40	605	891	487	----------	----------
50	686	----------	589	----------	----------

To show the amount of water removed from the tanks by the flumes expressed in depth in inches on an area equal to the cross section of the flumes, Table 27 is presented.

At the end of the thirtieth day it was found that the flumes had taken from the tanks sufficient water to cover the cross section of the flumes to a depth of from 16 to 40 inches. That is, where the rate of loss is the same over the area of an acre as over the area represented by the flumes, then in 20 days the acre of soil represented in flume 39 would have removed from the underground water 16.78 acre-inches of water, while the soil represented by flume 96 would have removed 39.65 acre-inches of water, or a little more than twice as much. These tables are valuable in that they give an indication of the quantity of water that may be removed

TABLE 27.—*Water removed from the tanks by capillarity expressed in depth on an area equal to the cross section of the flume.*

Number of days.	Flume.				
	39	58	76	96	206
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1	4.58	6.41	3.05	6.71	4.27
3	7.93	9.15	4.88	12.20	5.49
5	9.44	11.59	6.10	16.47	6.41
10	11.59	14.03	8.54	23.79	8.24
15	13.42	15.56	10.37	29.28	9.00
20	14.95	17.08	12.51	34.16	9.61
30	16.78	19.83	15.99	39.65	----------
40	19.06	22.42	20.13	----------	----------
50	21.35	25.01	24.40	----------	----------

from underground water sources by capillary action of the soil. It must be kept in mind, however, that in the case of the flumes evaporation and capillarity are acting at the same time.

DISTRIBUTION OF MOISTURE.

The distribution of moisture in the flumes inclined upward at an angle of 15° does not differ materially from the distribution in the vertical flumes. In Table 28 is given the distribution of moisture in flume 96 at various times. It will be noticed that in this table, as in that for the vertical flumes, there is rather a uniform constant quantity of moisture near the lower end and then a gradually decreasing amount toward the top of the flume. The rates of decrease, however, are not comparable as far as the figures in this table and those for the other flumes indicate.

TABLE 28.—*Distribution of moisture in flume 96.*

Distance.	Percentage of water.		
	Top 5 inches.	Bottom 5 inches.	Average.
Inches.	*Per cent.*	*Per cent.*	*Per cent.*
28	28.32	29.66	28.99
40	28.56	27.89	28.82
52	26.70	26.26	26.48
64	24.83	24.87	24.85
76	25.06	24.20	24.63
88	21.71	21.96	21.83
94	20.58	20.95	20.77
100	17.25	17.73	17.49

In the open flumes there are several factors which account for a lack of uniformity in the distribution of moisture other than the mere fact of elevation above the surface of the water. The rate of evaporation is different for different points of the flume due to differences in moisture content of the soil (18). The concentration at the surface of the soluble salts of the soil, which will be different at different points throughout the flume, would cause some difference in the moisture content due to lessening evaporation.

EFFECT OF GRAVITY ON THE MOVEMENT OF SOIL MOISTURE BY CAPILLARITY.

As stated in this report, the plan was to have capillarity act in the direction of gravity, in a direction opposed to gravity, and in a horizontal direction in which gravity was eliminated as far as possible. To give an idea of the influence of gravity in the movement of soil moisture by capillarity there are given below data on a complete set of flumes containing the heavy Riverside soil. While the other soils show considerable variation, these variations are almost entirely in degree and it is not thought that the addition of these data to this report would be of any material benefit. Table 29 gives a list of the flumes in the set under consideration and their angles relative to the horizontal.

TABLE 29.—*Number of flume and angle of inclination.*

No. of flume.	Angle of inclination.
34	30° downward.
32	15° downward.
31	Horizontal.
39	15° upward.
42	45° upward.
43	Vertical.

There was in this set an additional flume inclined downward at an angle of 45°, but the results from that flume were so near like those of the flume inclined at an angle of 30° downward that the addition of the data from this flume would be confusing without adding to the value of the information. In fact, the flume inclined downward at an angle of 45° was discarded after the third set of experiments, for the reason that it did not add to the information obtained from the flume inclined downward at 30°.

Figure 6 gives the results of the daily measurements of the movement of moisture in the several flumes. Table 30 gives the distance the moisture had moved at different periods of time from 1 to 40 days.

TABLE 30.—*Distance moisture had moved at various times, in flumes placed at different angles.*

Days.	Flume.					
	34	32	31	39	42	43
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1	26.00	22.05	20.00	16.35	16.75	15.70
3	44.15	41.30	33.75	24.55	24.40	20.75
5	58.25	55.00	41.20	28.55	28.85	22.82
10	91.05	8.85	53.30	35.80	32.90	26.25
15	118.65	105.20	61.40	40.25	34.65	28.05
20	144.05	125.45	66.15	43.65	36.05	29.40
30	181.25	153.55	75.80	48.40	37.50	31.55
40	....	168.35	79.85	51.25	38.75	33.15

Table 30 and figure 6 show very strikingly the effect of gravity on the capillary movement of soil moisture even at the end of the first day. It is obvious that in the horizontal flume the distance the moisture had moved is less than in either of the flumes inclined downward and is greater than for those inclined upward. This relation holds true not only for the first day but for all the time up to 40 days. The table shows that the movement of moisture is less extended in flumes inclined downward 15° than it is in flumes inclined downward 30°, but that the difference is not nearly so marked as is the difference between the 30° flume and the horizontal one. Flumes 31 and 32 show very clearly the effect of a relatively slight inclination downward from the horizontal.

For instance, on the thirtieth day the moisture has moved in flume 32 a little more than twice as far as in flume 31. The figures presented above and the figures obtained for the flumes inclined downward at an angle of 45° indicate that at least after an angle of 15° is obtained the effect of inclination is not nearly so marked, degree by degree, as for the first 15° of inclination. Comparing the horizontal flume with the flume inclined upward, we find that even on the first day the inclination is a marked factor in the extent of the movement

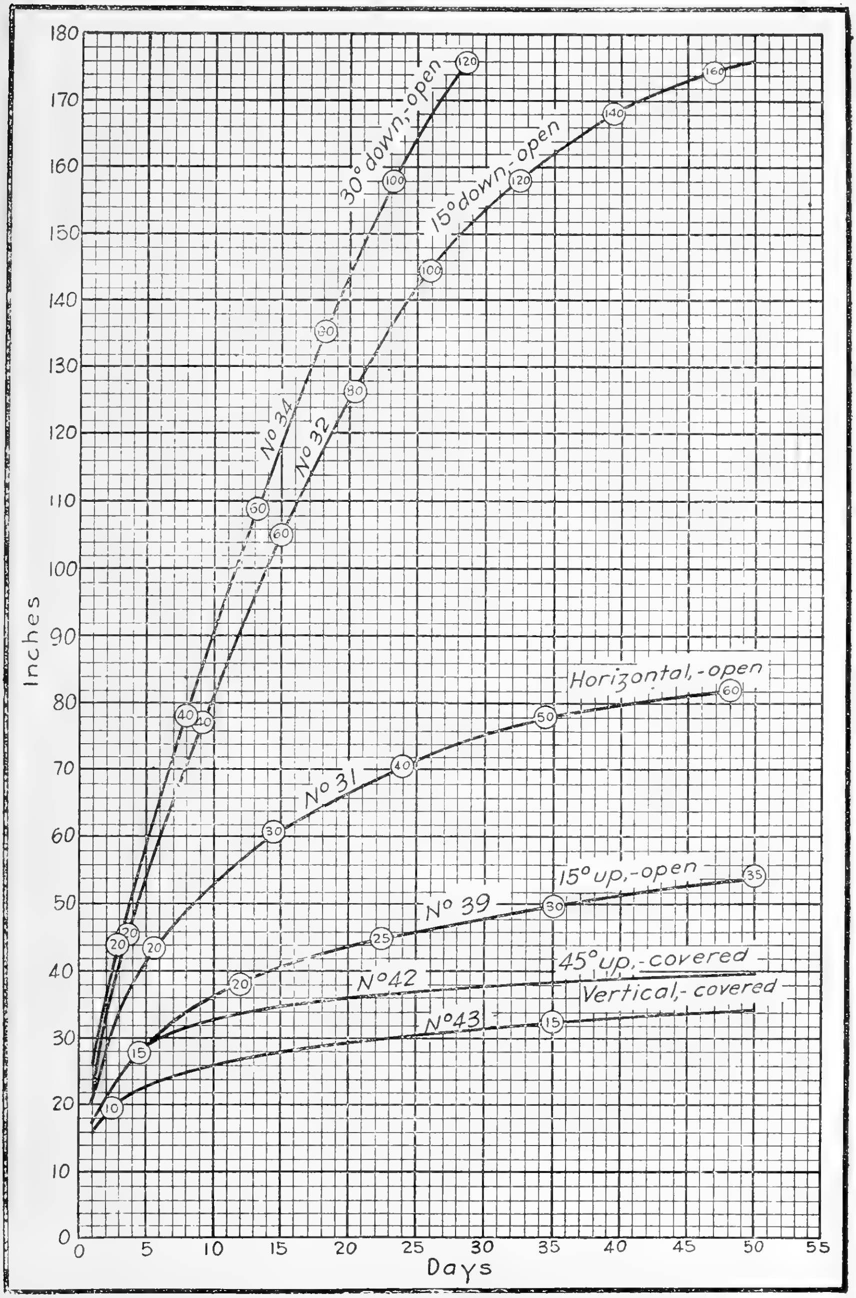

Fig. 6.—Rate of movement of moistue in set of flumes at various slopes each containing Riverside heavy decomposed granite loam soil. Figures within circles indicate point at which that number of liters of water had been taken up.

of the soil moisture. At the end of the thirtieth day we find that the flume inclined upward at 45° gives only one-half as extensive a movement of the soil moisture as the horizontal flume, and the flume inclined upward at an angle of 30° gives about two-thirds as extensive a movement of the soil moisture. Taking the four flumes, the horizontal, the one inclined upward at 30°, the one inclined upward at 45°, and the vertical flume, the extent of soil moisture in distance within these flumes is in the order given, with the greater extent of moisture in flume 31 or the horizontal flume.

To show more clearly the effect of gravity upon the movement of moisture by capillarity, Table 31 gives the data of Table 30 in percentages of movement in the flume inclined downward 30°:

TABLE 31.—*Relative movement of moisture in flumes, expressed in percentages of movement in flume 34.*

Number of days.	Flume.					
	34	32	31	39	42	43
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	100	85	80	63	61	60
3	100	93	76	56	55	47
5	100	94	71	49	49	39
10	100	90	59	39	36	29
15	100	90	52	33	29	24
20	100	87	46	30	25	20
30	100	85	42	26	21	12

On the thirtieth day we find that the moisture in the vertical flume has moved but 12 per cent as far as in flume 34 and in flume 42 it has moved 21 per cent as far; in flume 39, 26 per cent as far; in flume 32, 85 per cent as far; and in flume 31, 42 per cent as far. It is obvious that the above percentages are comparable to the angles of inclination relative to the horizontal. This table brings out even more strikingly the effect of gravity in the movement of soil moisture by capillarity.

Table 32 gives the relative distance the moisture had moved in the several flumes for different periods of time, based on the distance the miosture had moved in 30 days in the respective flumes.

TABLE 32.—*Capillary movement of moisture at various times, in percentage of the movement in 30 days.*

Number of days.	Flume.					
	34	32	31	39	42	34
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
1	14	14	26	34	45	50
5	32	36	54	59	77	72
10	50	53	70	74	88	83
15	65	68	81	83	92	90
20	79	79	87	90	96	93
30	100	100	100	100	100	100

The striking feature of Table 32 is the fact that as the flumes recede from the vertical the rate of movement day by day is more uniform and more constant. In the flume inclined downward at an angle of 30° the extent of movement of moisture on the fifteenth day or one-half the time was 65 per cent of the total movement of the moisture in 30 days. In flume 32 this percentage was 68. In flume 31 or the horizontal flume it was 81 per cent; in flume 39 it was 83 per cent; and in the flume with a vertical angle of 45° it was 92 per cent.

To present the above data in a more condensed form, figure 7 has been prepared.

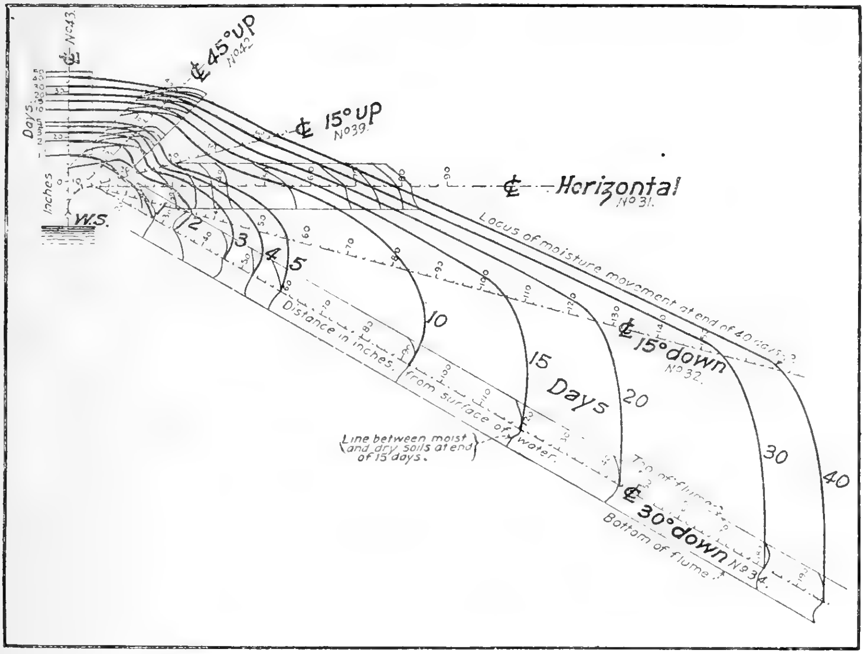

FIG. 7.—Comparison of rate of movement of moisture in flumes of various slopes; all flumes containing Riverside heavy decomposed granite loam. Also shows appearance of moisture curves from top to bottom of flumes, except Nos. 32 and 39.

Figure 7 shows the relative positions of the moisture in the various flumes with reference to the surface of the water in the tanks at various times during the experiment. The lines on the drawing showing the direction of the flumes represent the longitudinal axes of the flumes along their center lines. The figures show the directions and the paths through which the moisture from the tanks must travel along the center lines of the flumes. It is obvious that during the forepart of the experiment the lines joining the points representing the positions of the moisture on the different dates are very irregular. It shows that there is a tendency of the curve joining these

points to become more uniform in outline as the experiment continues for longer periods of time. That is, the line joining the points representing the position of the moisture on the thirtieth day is more regular and uniform than is the line joining the points for the position of the moisture on the first day. The figure indicates that with the lapse of an extended period of time the line joining the points representing the extreme extent of moisture would be of a parabolic form. This curve would have a rather limited extent in the vertical direction upward, but the longitudinal extent and the extent downward from the vertical might be infinity. Even with evaporation a factor, these last two named distances are relatively very great as compared with the vertical elements. The drawing emphasizes and portrays more clearly than do the figures the importance of gravity in the movement of soil moisture by capillarity. These deductions are of importance from the economic point of view in that they show very clearly what may be the distribution of moisture within the soil of water applied upon sloping ground. It indicates, for instance, that the extent of distribution of moisture down a slope would be much greater than it would be up a slope. A comparison of the data for these flumes indicates how great would be the loss of water in conveying channels through capillary action where the conveying channels traverse ground having a transverse slope. These data would indicate that on the lower side of the channel capillary action would continue taking water from the channel in about the same quantity for an indefinite period of time, while on the upper side the loss of water through capillarity would be very much less in quantity and in extent of time through which it would act. These figures indicate further the importance of slope of the strata of alluvial soil, both in reference to conveying channels and impounding reservoirs. In other words, these data indicate that with any appreciable slope downward of the strata, capillary action continues indefinitely.

WATER USED.

In considering the quantity of water used by the several flumes from the vertical upward to the 45° downward from the horizontal, it is found that the inclination of the flume is a most potent factor in determining the quantity of water that will be removed from the tanks. The data for these flumes indicate clearly the effect of gravity in the movement of water as soil moisture by capillary action. A difference in inclination may mean, and most frequently does mean, a difference between practically no movement of soil moisture and a movement of an appreciable relatively constant quantity of water.

The figures within the small circles in figure 6 give in liters the quantity of water removed from the tanks.

An examination of these data shows that the flumes inclined upward from the horizontal use a relatively large quantity of water during the first two or three days and that after that time a relatively small quantity of water. Near the end of the 30-day period very little water is taken up by these flumes. With the flumes inclined downward from the horizontal a somewhat larger quantity of water is used during the first three or four days than thereafter. However, these flumes after about the fourth or fifth day use a rather constant uniform quantity of water for an indefinite period of time within the limits of these tests. Table 33 gives the total quantity of water in liters used by the several flumes for different periods of time and shows in a more condensed form the data presented in figure 6, and that on the thirtieth day a vertical flume had used but 15 liters of

TABLE 33.—*Total quantity of water used at various times, in liters.*

Number of days.	Flume.					
	34	32	31	39	42	43
1	10.0	9.5	10.0	7.5	10.0	7.0
3	20.0	18.0	16.0	13.0	14.0	10.5
5	29.0	25.0	19.0	15.5	16.0	11.1
10	48.5	42.0	26.0	19.0	19.0	12.4
15	67.5	59.0	31.5	22.0	21.5	13.5
20	87.5	78.5	36.5	24.5	23.75	13.8
30	124.0	112.0	45.0	27.5	28.5	15.0
40	150.0	140.5	53.0	31.25	30.5	15.8

water, while a flume inclined downward at an angle of 30° had used 124 liters, or about eight and a third times as much. The table also shows that, with the exception of flumes 39 and 42, the quantity of water used by each flume was in the order represented by the inclination of the flume from the vertical downward. This table shows that for the flumes inclined downward at angles of 15° and 30° there was not such a great difference in the total quantity of water used. In other words, it would appear that for the flume inclined downward at an angle of 15° the capacity of the wick to furnish moisture to the flume from the tank had been about reached. In the two flumes 39 and 42, or those inclined up at an angle of 15° and 45°, respectively, we find not much difference in the quantity of water used. Just why this condition does exist in this case, there are not sufficient data to indicate clearly. However, flume 42 contains a relatively higher per cent of moisture than does flume 39. This of itself is not quite sufficient to account for the difference.

On the fortieth day flume 43 had removed from the tank the equivalent of 9.64 inches, and flume 34 had removed the equivalent of 91.58 inches. These figures are striking in that they show what effect the

slope of the ground has in assisting capillarity to draw water from conveying channels and storage reservoirs.

TABLE 34.—*Quantity of water removed from the tanks at various times, expressed in depth, on an area equal to cross section of flume.*

Number of days.	Flume.					
	34	32	31	39	42	43
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1	6.11	5.65	6.11	4.58	6.11	4.28
3	12.22	10.99	9.76	7.93	8.54	6.41
5	17.72	15.26	11.59	9.46	9.76	6.77
10	29.61	25.64	15.86	11.59	11.59	7.56
15	41.20	36.02	19.22	13.42	12.81	8.54
20	53.40	47.90	22.28	14.95	14.50	9.16
40	91.58	85.75	32.33	19.06	18.63	9.64

Table 35 gives the number of cubic centimeters of moisture required to advance the moisture in the flumes an average distance of 1 inch at different periods of time. One point worthy of note in this table is the fact that flume 43 used about the same quantity of water per inch throughout. It must be kept in mind that this flume was closed to evaporation and that no water escaped from this tank that was not confined within the wetted soil area of the flume. The other flumes were all open to evaporation. The figures seem to indicate that as we recede from the vertical the quantity of water required per inch is less. However, these figures are so confused with the evaporation that they do not indicate the true facts as to the requirement of the soil itself when placed at these different angles. The evaporation factor is confused, for the reason that the soil within the flume contains relatively different percentages of moisture, which has an influence upon the quantity of evaporation. Furthermore, the wetted area of soil differs so greatly in the several flumes and hence that the area exposed to evaporation is much different.

TABLE 35.—*Average quantity of water required to advance wetted area in flumes 1 inch.*

Number of days.	Flume.					
	34	32	31	39	42	43
	c. c.	*c. c.*	*c. c.*	*c. c.*	*c. c.*	*c. c.*
1	385	419	500	406	596	446
3	447	436	474	530	573	506
5	498	455	477	543	578	486
10	533	513	488	531	587	482
15	569	561	501	556	629	487
20	608	626	562	573	663	471
30	684	739	616	548	760	476
40	....	843	681	605	767	476
50	....	....	....	686	....	....

EVALUATION OF EMPIRICAL CURVES.

In order to determine whether any mathematical relation could be found between the curves representing the movement of moisture in the different soils, mathematical equations to fit these empirical curves were found for typical flumes. The curves representing the movement of moisture in flumes at various slopes containing Riverside heavy decomposed granite loam were evaluated to ascertain whether the movement of moisture was a function of the angle of the slope.

The problem of finding a mathematical equation to fit a given curve is a tedious one. Since many soil physicists are perhaps unfamiliar with methods of procedure other than by the method of least squares, which is so laborious as to limit its application, the method which was used to derive these formulæ is explained in detail for two of these, one of which is a simple case and the other much more complicated. The method used is that explained in Engineering Mathematics, C. P. Steinmetz, New York, 1917, pages 209–274, to which reference is also made for an explanation of the properties of different curves.

In the following description, the number of days on which the moisture position was observed is denoted by x and the position of advancing moisture measured in inches above the water surface is denoted by y. The corresponding values of x and y were tabulated and plotted as a curve. It is apparent that the curve in every instance must pass through the origin, for when $x=0$, $y=0$, and the nature of the problem also suggests that the curve be in the form of a parabola. This was found to be true in the majority of cases, but, as will be seen in the formulæ given on a subsequent page, the curve law in some instances changed within the range of the observations.

Curves which are represented by $y=ax^n$ are parabolic or hyperbolic curves passing through the origin. When n is positive, the curve is parabolic. When n is negative, the curve is hyperbolic.

The logarithm of the equation $y=ax^n$ is $\log y=\log a+n \log x$, which is a straight-line formula. If the curve resulting from the plotting of the logarithm of y against the logarithm of x is a straight line, the curve representing the data is a parabola or hyperbola.

The equation for the exponential curve is $y=a\varepsilon^{nx}$, which usually occurs with negative exponent in the form $y=a\varepsilon^{-nx}$, which gives $\log y=\log a-nx \log \varepsilon$. Log y is a linear function of x and plotting log y against x, or log x against y, gives a straight line. Thus plotting log y and log x and x and y against each other permits the form of curve to be recognized. If constant terms exist, the logarithmic

line is curved. By trying different constants, the logarithmic line changes in curvature, so that such constants may be found which make the logarithmic line straight.

Logarithmic cross-section paper may be purchased which has both coordinates divided in logarithmic scale and also semilogarithmic cross-section paper having one ordinate so divided. When evaluations of equations having constant terms are to be made, these papers are very convenient, since the curves may be plotted without looking up the logarithms; but since the method described by Steinmetz

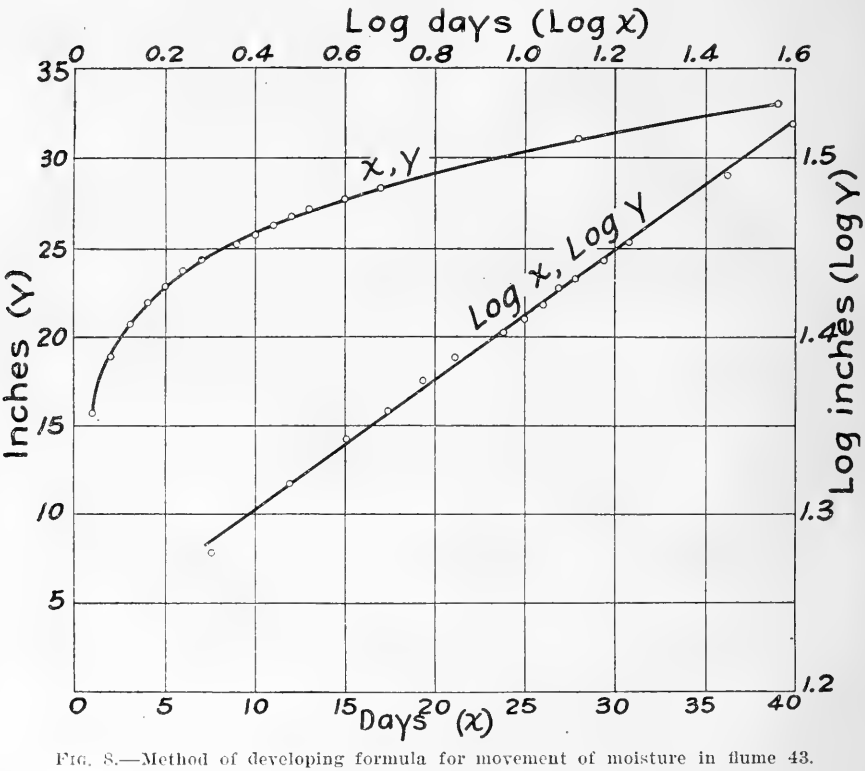

FIG. 8.—Method of developing formula for movement of moisture in flume 43.

requires logarithms to be tabulated in order to calculate the constants, common cross-section paper will usually suffice.

In figure 8 the data representing moisture movement in flume 43 are plotted. The values of log y and log x are also plotted and found to be a straight line, so that log y=log $a+n$ log x and the curve is a parabola. Table 36 gives the data, the logarithms of x and y and the calculated log y as obtained from the formula which was derived.

TABLE 36.—*Flume 43.*

x days.	y inches.	Log x (log days).	Log y (log inches).	1.224 +.186 log x.	y_c* (inches).	Δ
1	15.70	0	1.196	1.224	16.75	+1.05
2	18.95	.301	1.278	1.280	19.05	+0.10
3	20.75	.477	1.317	1.313	20.56	−0.19
4	22.00	.602	1.342	1.336	21.68	−0.32
5	22.82	.699	1.358	1.354	22.59	−0.23
6	23.75	.778	1.376	1.369	23.39	−0.36
7	24.45	.845	1.388	1.381	24.04	−0.41
9	25.25	.954	1.402	1.402	25.24	−0.01
10	25.75	1.000	1.411	1.410	25.70	−0.05
11	26.25	1.041	1.419	1.419	26.25	0.00
12	26.75	1.079	1.427	1.425	26.61	−0.14
13	27.15	1.114	1.434	1.431	26.98	−0.17
15	27.75	1.176	1.443	1.443	27.75	0.00
17	28.37	1.230	1.453	1.453	28.37	0.00
28	31.00	1.447	1.491	1.493	31.12	+0.12
39	33.00	1.591	1.519	1.520	33.11	+0.11
48	34.00	1.681	1.531	1.536	34.36	+0.36
50	34.75	1.699	1.541	1.540	34.68	−0.07

* y_c, distance in inches computed by using the formula derived for flume 43.

The 18 sets of observations are divided into two groups of 9 each. The sum of the first 9 log x and log y are found, together with the second group of 9. These are indicated as Σ9 in the computations. Since the formula log y= log a + n log x applies to all parts of the curve, it is the same for the two groups, subtracting the two groups from each other eliminates log a and dividing the one difference Δ by the other gives the exponent n,

$$n = \frac{\log y_2 - \log y_1}{\log x_2 - \log x_1}$$

The sum of all the values of log x, Σ_{18}, is found and multiplied by n, and the product subtracted from the sum of all the log y, log a = log y—n log x. The difference, Δ, is divided by 18 and the quotient is the log a.

The actual computations for the above case are as follows:

$$\log x\ \Sigma_9 = 5.657 \qquad \log y\ \Sigma_9 = 12.068$$
$$\Sigma_9 = 12.060 \qquad \Sigma_9 = 13.259$$
$$\Delta = 6.403 \qquad \Delta = 1.191$$

$$n = \frac{1.191}{6.403} = 0.186$$

$$\log x\ \Sigma_{18} = 17.716 \qquad \log y\ \Sigma_{18} = 25.327$$
$$17.716 \times 0.186 = \qquad 3.295$$
$$\Delta = \qquad 22.032$$
$$22.032 \div 18 = 1.224 = \log a$$
$$a = 16.75$$
$$y = 16.75x^{0.186}$$

TABLE 37.—*Flume 31.*

x (days)	y (inches)	log x (log days)	log y (log inches)	y_1	$y_2=y_1-y$	log y_2	$y_2+5.5$	log ($y_2+5.5$)	9.631 +1.06 log x	y_c* = 21.39 $x^{0.4}$ — (0.43 $x^{1.06}$ —5.5)	Δ
1	20.00	0	1.301	20.00	0	0	....	....	....	....	....
2	28.45	.301	1.454	28.21	—.24	$\bar{9}$.380	....	....	....	....	....
3	33.75	.477	1.528	33.96	.21	$\bar{9}$.322	....	....	....	....	....
4	37.90	.602	1.579	37.24	—.66	$\bar{9}$.820	....	....	....	....	....
5	41.20	.699	1.615	40.71	.51	$\bar{9}$.708	....	....	....	....	....
6	44.60	.778	1.649	43.80	—.40	$\bar{9}$.602	....	....	....	....	....
7	47.00	.845	1.672	46.59	—.41	$\bar{9}$.613	....	....	....	....	....
8	49.15	.903	1.692	49.14	—.01	0	....	....	....	....	....
9	51.30	.954	1.710	51.51	.21	$\bar{9}$.322	....	....	....	....	....
10	53.30	1.000	1.727	53.73	.43	$\bar{9}$.633	....	....	....	....	....
11	55.60	1.041	1.748	55.81	.21	$\bar{9}$.322	....	....	....	....	....
12	57.50	1.079	1.750	57.79	.29	$\bar{9}$.462	....	....	....	....	....
13	59.05	1.114	1.771	59.67	.62	$\bar{9}$.792	6.12	.793	.812	58.68	—0.37
14	60.03	1.146	1.778	61.47	1.44	.158	6.94	.841	.846	59.96	—0.07
15	61.40	1.176	1.788	63.19	1.79	.253	7.29	.863	.878	61.14	—0.26
16	62.35	1.204	1.794	64.84	2.49	.396	7.99	.903	.907	62.37	+0.02
17	63.25	1.230	1.801	66.43	3.18	5.07	8.68	.939	.935	63.32	+0.07
18	64.15	1.255	1.807	67.97	3.82	.582	9.32	.969	.962	64.31	+0.16
19	65.20	1.279	1.814	69.46	4.26	.629	9.76	.989	.987	65.26	+0.05
20	66.15	1.301	1.821	70.89	4.74	.675	10.24	1.010	1.010	66.15	0.00
21	67.10	1.322	1.827	72.29	5.19	.715	10.69	1.029	1.033	67.00	—0.10
22	67.90	1.342	1.832	73.65	5.75	.760	11.25	1.053	1.053	67.85	—0.05
24	69.35	1.380	1.841	76.26	6.91	.840	12.41	1.094	1.094	69.34	—0.01
25	70.30	1.398	1.847	77.51	7.21	.858	12.71	1.104	1.114	70.01	—0.29
27	71.45	1.431	1.854	79.94	8.49	.929	13.99	1.146	1.148	71.38	—0.07
29	72.60	1.462	1.861	82.25	9.65	.985	15.15	1.180	1.181	72.58	—0.02
30	73.02	1.477	1.863	83.38	10.36	1.015	15.86	1.200	1.196	73.18	+0.16
32	74.35	1.505	1.871	85.56	11.21	1.050	16.71	1.223	1.226	74.23	—0.12
35	75.80	1.544	1.880	88.68	12.88	1.110	18.38	1.264	1.267	75.69	—0.11
38	77.25	1.580	1.888	91.64	14.39	1.158	19.89	1.299	1.306	76.91	—0.34
43	78.90	1.633	1.897	96.29	17.39	1.240	22.89	1.300	1.363	78.72	—0.18
46	79.95	1.663	1.903	98.93	18.98	1.278	24.48	1.389	1.394	79.66	—0.29
49	80.60	1.690	1.906	101.45	20.85	1.319	26.35	1.421	1.423	80.48	—0.12
55	81.90	1.740	1.913	106.25	24.35	1.387	29.85	1.475	1.475	81.90	0.00

* y_c, distances in inches computed by using the formula derived for flume 31.

In table 37 are given the data obtained from flume 31, the logarithms of x and y being tabulated. Figure 9 shows that the logarithmic curves between log x, log y, and x and y are not straight, so that the curve is not a simple parabola or exponential curve. The curve between log x and log y is straight up to 12 days. Thus the curve is a simple parabola for values of x less than 12. The 12 sets of observations are divided into two groups of six each and the formula derived as explained for flume No. 42.

$$\begin{array}{rl} \log x\ \Sigma_6 = 2.857 & \qquad \log y_1 \Sigma_6 = 9.126 \\ \Sigma_6 = 5.823 & \qquad \Sigma_6 = 10.308 \\ \Delta = 2.966 & \qquad \Delta = 1.182 \end{array}$$

$$n = \frac{1.182}{2.966} = 0.40$$

$$\begin{array}{rl} \log x\ \Sigma_{12} = 8.680 & \qquad \log y_1 \Sigma_{12} = 19.435 \\ 8.680\ xn = & \qquad 3.472 \\ & \qquad \Delta = 15.962 \end{array}$$

$$15.962 \div 12 = 1.330 = \log a$$

$$\log y_1 = 1.330 + 0.40 \log x$$

$$y_1 = 21.39\ x^{0.4}$$

The values of y_1 are calculated from this formula and tabulated in Table 37.

The differences between y_1 and y are also tabulated as y_2. $y_2 = y_1 - y$.

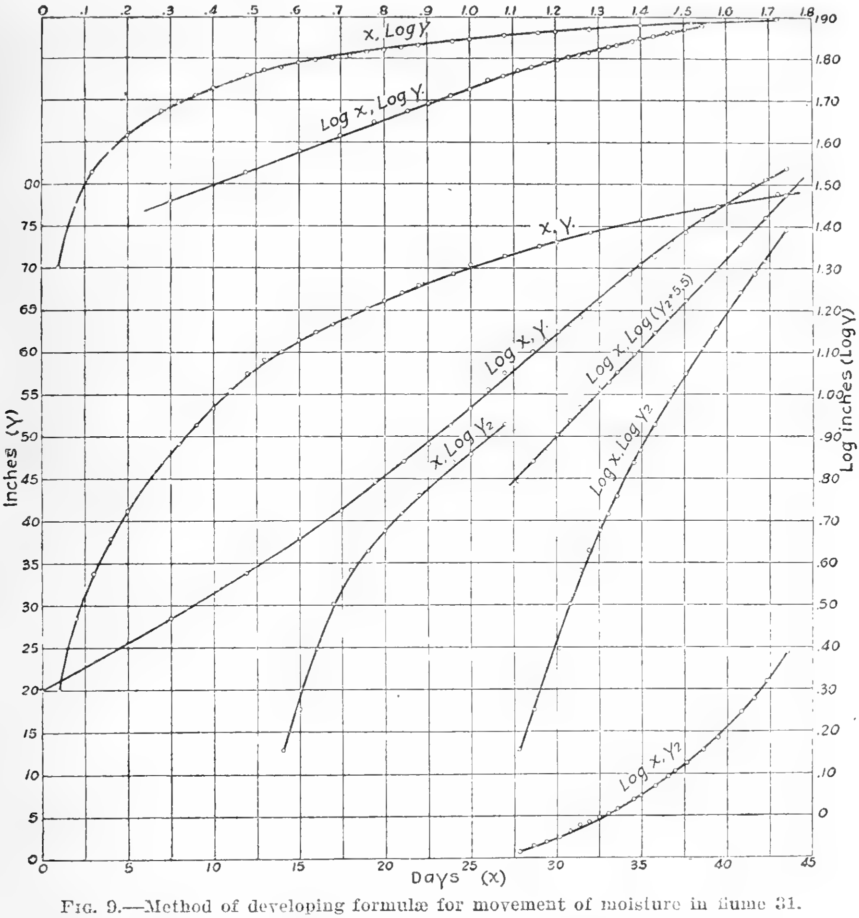

FIG. 9.—Method of developing formulæ for movement of moisture in flume 31.

The values of y_2, log y_2, log y_1 x, log x, and y are plotted against each other as shown in figure 9 A, but none of these curves is a straight line. This suggests the existence of a constant term, and a number of constants were tried until it was found that the curve between log $(y_2+5.5)$ and log x is a straight line. The curve above 12 days or $12x$ then is log $(y_2+5.5) = \log a + n \log x$.

The remaining 22 sets of observations were divided into two groups, and the equation of this parabola was derived as follows:

$$\log x\ \Sigma_{11}=13.751 \qquad \log\ (y_2+5.5)\Sigma_{11}=10.481$$
$$\Sigma_{11}=\underline{17.124} \qquad \Sigma_{11}=\underline{14.061}$$
$$\Delta\ =\ 3.374 \qquad \Delta\ =\ 3.579$$
$$n\ =\frac{3.579}{3.374}=1.06 \qquad \log\ (y_2+5.5)\ \Sigma_{22}=24.542$$
$$30.875\times 1.06=32.666$$
$$\log x\ \Sigma_{22}=30.875 \qquad \Delta\ =\ 1.876-10$$

$$1.876-10\div 22=9.631-10=\log a$$
$$\log\ (y_2+5.5)=9.631-10+1.06\ \log x$$
$$y_2=0.43\ x^{1.06}-5.5$$
$$\text{Since } y_2=y_1-y,\ y=y_1-y_2$$
$$\text{then } y=21.39\ x^{0.4}-(0.43x^{1.06}-5.5)$$

The values calculated from this equation are tabulated and the differences from the values of y as obtained in the experiment are noted.

When the curve resulting from the plotting x or y against log x or log y is straight, the exponential curve is derived in the same manner as for a parabola. The data are divided into two groups and the value of n and log a found.

log y=log a—nx log ε represents the equation for both groups, so that log a can be eliminated by subtracting one from the other.

$$n=\frac{\log y_1-\log y_2}{\log \varepsilon\ (\log x_2-\log x_1)}\ \text{in which } \log \varepsilon=0.4343$$

$$\log a=\log y-nx \log \varepsilon$$

In several cases it was found that for high values of x and y the curves were straight lines and the equations for these straight lines found.

Subtracting the values of y_1 in the equation $y_1=mx+b$ from the y values of the data gave values of y_2.

The log y_2 plotted against x gave straight lines, so that the curve for these low values of x and y were exponential curves which were derived as explained above.

The formulæ for the curves representing moisture movement in the flumes held at different angles when filled with Riverside heavy decomposed granite loam (Placentia loam) were as follows:

Flume No. 42 (45° up):

$$y=33.7+0.12x-(18.5\varepsilon^{-0.2x})$$

Flume No. 32 (15° down):

$$y=21.44x^{0.59}-(0.026x^{1.92}-11)$$

Flume No. 34 (30° down):

$$y=22.24x^{0.62}$$

Flume No. 39 (15° up):

$$y=18.36x^{0.28}$$

Flume No. 31 (horizontal):

$$y=21.39x^{0.4}-(0.43x^{1.06}-5.5)$$

Flume No. 43—(vertical up):

$$y=16.75x^{0.19}$$

The following equations were found for other flumes and soils:

Flume No. 33 (15° down) Riverside heavy decomposed granite loam (Placentia loam) Riverside, Calif.

$$y=5.1x+21.-(18.25\varepsilon^{-0.85})$$

Flume No. 61 (45° up) Dublin clay loam, near Whittier, Calif.:

$$y=0.21x+23.7-(15.5\varepsilon^{-0.19}x)$$

Flume No. 51 (horizontal) Dublin clay loam, near Whittier, Calif.:

$$y=11.23x^{0.37}$$

Flume No. 59 (15° up) Dublin clay loam, near Whittier, Calif.:

$$y=15.21x^{0.28}$$

Flume No. 40 (15° up) Riverside heavy decomposed granite loam (Placentia loam) Riverside, Calif.:

$$y=20.53x^{0.31}$$

Flume No. 30 (horizontal) Riverside heavy decomposed granite loam (Placentia loam) Riverside, Calif.:

$$y=20.89x^{0.47}$$

Flume No. 35 (30° down) Riverside heavy decomposed granite loam (Placentia loam), Riverside, Calif. (for values of x greater than 8, curve is straight line):

$$y=7.3x+12$$

These equations could be used to determine the position of the moisture at some time beyond the range of observation of the experiment if it is assumed that the curve law does not change for higher values of x.

Dr. R. H. Loughridge, in the Report of the College of Agriculture of the University of California for the years 1892, 1893, and part of 1894, pages 91 to 100, gives the observed position of moisture in a column of Ventura County tilled soil (silt loam). These observations extended for a period of 195 days, which is one of the longest periods that has been reported in literature. The formula $y=13.9x^{0.24}$ represents the movement of this moisture and there is no change in the curve throughout the period of observation. Values of y calcu-

lated from this formula agree with sufficient accuracy with the observed values of y.

Dr. Loughridge states that the limit of moisture movement was reached at the end of 195 days at 50 inches. It is interesting to note that the position of the moisture at the end of one year as calculated from the formula would be 56.2 inches; at 390 days, twice the time of observation, 57 inches; two years at 66.2 inches; and three years, 72.9 inches, or only 22 inches above what it was at the end of 195 days.

OPEN VERSUS COVERED FLUMES.

The results obtained from the covered flumes are very similar to those obtained from the flumes open on top to evaporation. With one or two exceptions the results with the covered flumes do not differ materially from what could have been foreseen from the results with the open flumes. The essential difference is one of degree, as would have been expected. One striking exception is the fact that in every instance of the 25 or 30 experiments the open flume has the more rapid rate of movement of the moisture for the first one to five weeks of the experiment, the difference in time depending upon the character of the soil. The heavier the soil and the longer the open flume maintained the more rapid rate of movement of the moisture. The more rapid rate of movement is maintained irrespective of evaporation. This fact will be more clearly seen from the data submitted below. There is, as would be expected, a small difference in the relative percentages of moisture contained in two flumes, and especially is this difference noticeable in the upper layers of soil.

Inasmuch as the results with the covered flumes differ only in degree from those of the open flumes, it is not deemed that the submission of all the data and its discussion would add materially to the value of this report. For that reason there will be discussed only one covered flume in its relation to its comparable open flume. The two flumes that will be presented in detail are the horizontal flumes 70 and 71 containing the soil from Upland. This is a gravel and sand soil containing but little clay. The selection of this particular soil for presentation is merely for convenience, as the results obtained by its use are similar to the results obtained from other soils, figure 3 (p. 23) shows the curves representing the movement of moisture in these two flumes.

Table 38 gives the total movement of moisture in these two flumes at the end of various periods of time. From this table it will be observed that flume 70, which is open to evaporation, has the more rapid rate of movement of the moisture up until the fifth day. After the fifth day flume 71, or the covered one, has a more extended movement of the moisture and upon the thirtieth day this difference is

about 9 per cent in favor of the open flume. The rate of movement of the moisture in the closed flume is more uniform throughout the 30 days than that in the open flume. The facts just stated would appear to be contrary to what might have been forecast, for the reason that evaporation from the open flume would deprive that flume of some of the water furnished by the wick. In the closed flume practically all of the water furnished by the wick would be available for the capillary action of the soil. These results would indicate first that in the closed flume the soil in the flume proper could not use all of the water that the wick was capable of furnishing. This would indicate a friction factor caused either from partially confined air or otherwise that would not appear to occur in the open flume. It is found in the open flume that either from evaporation or from a more ready circulation of the air the capillary action of the soil within the flume was stimulated or that the friction was reduced. From observations made in connection with other experiments it seems to the writer that the fact of more rapid rate of movement in the open flume at the beginning of the experiment is due to both of these factors. It is known that "trapped" air has an effect upon capillary action and that evaporation would stimulate the circulation of the air.

TABLE 38.—*Movement of moisture at various times, in inches.*

Number of days.	Flume.	
	70	71
	Inches.	*Inches.*
1	23.10	21.30
3		
5	41.70	41.30
10	54.60	54.80
15	64.00	65.50
20	70.15	73.70
30	80.05	87.10

TABLE 39.—*Quantity of water used at various times, in liters, and in percentages of total used in 30 days.*

Number of days.	Flume.			
	70	71	70	71
	Liters.	*Liters.*	*Per cent.*	*Per cent.*
1	6	6	18	21
3				
5	12	12	37	42
10	17	17	51	59
15	21	21	64	72
20	26	24	79	83
30	33	29	100	100

Table 39 shows that a relatively greater quantity of water was used by the closed flume during the forepart of the experiment than was used by the open flume. This is a condition which would be anticipated, as evaporation deprives the open flume of part of the water furnished by the wick. The table shows very clearly that the covered flume does not tax the wick to its capacity in furnishing water from the tank to the flume proper.

Table 40 gives the quantity of water required to move moisture in the flume an average distance of 1 inch for different periods of time. This table does not show effects other than would have been anticipated. It is observed that there is a greater use of water on the thirtieth day in flume 71 than during the fore part

of the experiment. This can be accounted for in two ways: First, all evaporation could not be eliminated without liability of trapping the air within the flume. Second, there is, as has been shown previously, an increase in the percentage of moisture contained in different portions of the flume with the age of the experiment.

Table 41 gives the use of water by these flumes in equivalent depth over an area equal to the cross section of the flumes.

TABLE 40.—*Water required at various times to advance moisture an average distance of 1 inch.*

Number of days.	Flume.	
	70	71
	c. c.	*c. c.*
1	259	281
5	288	291
10	311	310
15	328	321
20	371	326
30	412	333

TABLE 41.—*Water removed from tanks at various times, in depth.*

Number of days.	Flume.	
	70	71
	Inches.	*Inches.*
1	3.66	3.66
5	7.32	7.32
10	10.37	10.37
15	12.81	12.81
20	15.86	14.64
30	20.13	17.69

It is found that flume 70 used the equivalent of 20.13 inches of water in 30 days, while the covered flume (71) used the equivalent of 17.69 inches or about 12½ per cent less than the open flume. These figures show that for the last ten days of the experiment the open flume used 4.27 inches and the closed flume 3.05 inches or a little over 25 per cent less water than the open flume. These last figures would represent the effect of evaporation. In other words, during the last ten days of the experiment evaporation from the flume took care of at least 25 per cent of the water furnished by the wick.

EFFECT OF TEMPERATURE ON SOIL-MOISTURE CONDITIONS.

As has been stated previously, a temperature at and below the freezing point appears to have influenced to a marked extent the distribution of moisture within the flumes. Some few soil samples taken from the flumes during the winter of 1916–17 gave results contrary to what was to be expected. In the sampling of the flumes, two samples were taken from each point of sample. The soil from the top 5 inches was placed in one bottle and the soil from the bottom 5 inches in a second bottle and the moisture determined for each separately. There are two basic reasons why the percentage of moisture in the top samples should be less than that in the samples from the bottom 5 inches. First, the sample from the upper 5 inches

of soil is farther away from the water and gravity would tend to hold the moisture in the lower layer. Secondly, evaporation from the surface would tend to further reduce the moisture at and near the surface. Thus the laws of physics would indicate a lower percentage of moisture toward the top of the flume than near the bottom. There were, however, several instances where this relationship was interchanged, and more especially was this noticeable during the winter of 1916–17. When this interchanged relationship in the distribution of moisture was observed so frequently during the spring of 1917 as to almost preclude the probability of error from sampling, it seems evident that the unlooked-for distribution of moisture was the result of some natural condition. It soon became apparent that the top part of the flumes showed the greater percentage of moisture during only that time of the year when the air temperature was or recently had been below 30°. In looking back over the results of the preceding winter, this same condition was found. When these facts became evident it was so late in the season that there was no opportunity to prove the matter beyond a question of doubt. For this reason a few of the samples, with percentage of moisture and air temperature, are given in Table 42 for what they may be worth.

TABLE 42.—*Soil-moisture distribution and air temperature.*

Date.	Distance.	Flume.	Percentage of moisture.		Temperature for week preceding.	
			Top 5 inches.	Bottom 5 inches.	Maximum.	Minimum.
	Inches.		*Per cent.*	*Per cent.*		
Mar. 5, 1917	21	90	31.53	29.32	70°	27°
	38	....	27.44	36.30	....	....
	62	....	26.33	25.66	....	....
	92	....	23.37	23.67	....	....
	44	95	29.11	26.83	70°	27°
	128	....	27.78	26.64	....	....
	201	....	41.13	28.46	....	....
Mar. 16, 1917	32	92	28.75	30.44	77°	26°
	68	....	26.45	26.38	....	....
	104	....	25.75	25.45	....	....
	140	....	24.30	24.60	....	....
	190	....	17.83	19.32	....	....
Apr. 21, 1917	32	101	28.31	29.90	82°	32°
	72	....	20.61	22.00	....	....
	56	....	25.13	25.47	....	....

At a distance of 82 inches in flume 93 there was taken on March 20 a set of samples dividing the boring into four samples, each containing $2\frac{1}{2}$ inches of soil in depth, and the following results obtained:

In the top sample, 28.96 per cent.

In the second sample, 27.56 per cent.

In the bottom sample, 26.60 per cent.

In addition to the samples given above there are several others showing similar results. There are some samples taken at the same

time in the same flume that gave the natural distribution of moisture and the interchanged distribution. In these cases there was not as great a difference in the relative percentages of moisture at the top and bottom as where all samples showed the interchanged relation.

In the samples given above, it is noticed that this interchanged relation of the distribution of the moisture occurs in both the open and covered flumes. This same fact is true of all of the other work, except that the covered flumes seem to require a little lower temperature of the air to cause this result than do the open flumes. It will be noticed in Table 42 that with a relatively low percentage of moisture an interchange of the natural distribution of the moisture did not occur. It is probable that if such a distribution should occur, a temperature lower than 26° F. would be required. As shown in this table, for flume 101, with the minimum temperature of 32°, the upper part of the soil still contained a little less moisture than the bottom part of the soil. By comparing results shown for flume 101 with other samples taken with higher minimum temperatures, it is evident that a slight difference occurred in the normal distribution of the moisture in the samples.

Before a definite conclusion can be drawn, additional experiments will have to be made.

THE CAPILLARY SIPHON.

The definitions of capillarity and of capillary moisture used in so many of the old textbooks would lead one to conclude that free water would not be developed as a result of capillarity. For instance, the old illustration of the towel and the basin of water was used to combat the idea of free water as a result of capillarity. No reference to the probable fallacy of the old doctrine has been stated. In fact, all reference to the relation of gravity and capillary action, except as contained in the old original definition, has been in the most general terms. The prevalent method of disposing of the question is to say that capillary action is influenced by gravity. (1) There appears to be no statement as to any quantitative relation.

One of the very first sets of experiments tried at Riverside in the fall of 1915 included flumes inclined at angles of 15° and 30°, and one at 45°. The first of these had an ultimate total length of 20 feet and the last two had lengths of 10 feet each. The moisture in the flume inclined downward at 45° had reached the end of the flume in 18 days, and in the one inclined downward at 30°, the moisture had reached the end of the flume in 21 days. Three or four days after the moisture had reached the end of these flumes, free water was observed dripping from the ends of both. In about a week

after the moisture had reached the lower end of the flume inclined downward at an angle of 15° free water commenced dripping from the lower end. The water continued to drip from the ends of all three of these flumes for at least two weeks, or until the flumes were dismantled. It must be kept in mind that this water was raised from the tank a vertical distance of 4 inches by capillarity and against gravity. It was then transmitted down the flumes by means of the same force and in a direction with gravity. The moisture left the soil column at the lower end of the flume as free water, dropping to the ground. At no point in the entire length of the soil column, with the possible exception of the extreme lower end of the flume, was the percentage of moisture in the soil as great as that of capillary saturation, as measured by the general methods for determining this percentage. This, then, is in effect transferring water from a body of free water by capillarity and delivering it again as free water.

To supplement the results from the flumes and to test the further possibility of creating a capillary siphon, a special piece of apparatus shown in figure 10 was set up.

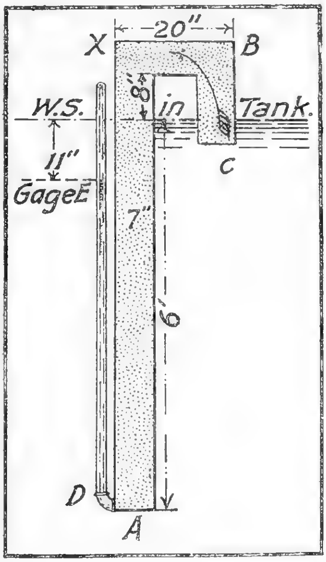

FIG. 10.—The soil column as a capillary siphon.

A–B in figure 10 is a galvanized-iron tube 7 by 7 inches in area and made in the shape shown. This box is water-tight and air-tight, except along the top *X–B*, at the bottom of the short arm at *C*, and at a point *D* at the bottom of the long arm. This tube stands vertical and rests on *A*. The top along the line *X–B* is open to the air. The lower end of the short arm at C has soldered over it a fine-meshed wire gauze. *D* is a $\frac{5}{8}$-inch ell soldered into the lower end of the long arm; the top of the ell is fitted with a water-gauge connection. Into the top of this ell is fitted a gauge glass *X–D*, on the outside of the tank or tube. The tube is packed with soil as indicated and the soil is exposed to the air along the line *X–B*. The short arm of the tube extends down into a tank of water represented by water line in tank.

It is observed from figure 10 that the high-water line in the tank is 8 inches below the bottom of the horizontal part of the tube. This 8 inches is then the distance the water must be raised from the tank before it can move horizontally. It must then move hori-

zontally an average distance of 12 inches before it can move downward.

The detailed measurements will not be given, but after 60 days the water in the gauge glass on the outside of the flume showed water up to a point within 11 inches of the surface of the water in the tank; that is, after 60 days that part of the tube below the point designated "Gage E" in gauge glass was completely saturated. After the sixtieth day, the rate at which the water rose in the gauge glass was very slow, and upon the seventieth the experiment was terminated.

This experiment, as did the previous ones cited, gave free water as a result of capillary action.

Three additional experiments were run with the same tube, but containing soils of a different type. In each case the same result was obtained, except that they were terminated sooner and for that reason the water did not rise so high in the glass.

Finally, it may be stated that in every flume, covered and open, that was inclined downward at an angle from 15° to 45° free water was developed when the experiment was run for a sufficient time. In only 3 or 4 instances out of the 20 or more flumes so inclined were the experiments terminated before free water was dripping from the lower ends of the flumes.

Several tests were made of the amount of water taken up from the tanks and delivered again at the lower end of the flumes as free water. One of these tests will be given.

The flume selected is No. 95, containing the lava soil from Idaho. This flume was covered, inclined downward from the horizontal at an angle of 30°, and was 15 feet in length. The records show that the flume commenced dripping water at the lower end on February 25, 1917. Commencing with March 1, the quantity of water lost from the tank by the wick was 18 liters. During this same period there was caught at the lower end of the flume 8.78 liters, or approximately 50 per cent of the quantity taken from the tank. The water was caught in a can as it dripped from the flume.

It has been suggested that a true siphon might have been formed as a result of "soil puddling" or other natural mechanical means. It did not occur in many cases and it is doubtful if it occurred at all. It is found, for instance, that with the use of clean, coarse building sand, devoid of clay or other fine material, the same result is obtained. However, to test this point further, a system of ventilation within the wick was installed.

Ventilating pads were made out of ordinary window-screen wire. From six to eight thicknesses of wire were rolled into a very small diameter and then flattened out. This made a pad of wire about

$2\frac{1}{2}$ inches in width and about three-eighths of an inch in thickness. The wire, when placed within the soil, kept the soil particles apart throughout most of the spaces occupied by the pad. Four of these wire pads were inserted vertically within the wick, extending from within about one-half inch of the water in the tank up through the wick of the flume to the air above. These pads were placed in the corners of the wick and about 1 inch from any side. The flume and wick were then packed with soil and the experiments started. With the flume inclined downward at an angle of 30°, and with the light sandy Idaho soil, water dripped from the end of the flumes in about four days and continued to drip until the experiment was discontinued. This experiment was repeated, and in addition to the vertical ventilating pads, two other pads were placed, one diagonally across the wick and one in a horizontal position. The ends of these pads butted against the vertical pads and were placed about 1 inch above the surface of the water of the tank.

This flume gave the same results as the other flume, but a little less water was taken from the tank in the case of the ventilated wicks than in the wicks not ventilated. However, free water dripped from the lower end of all of these flumes. In the wick having the vertical and horizontal pad ventilators (so called) there was no unventilated space within the wick at a greater distance than $1\frac{1}{2}$ inches from a ventilator.

In several of the flumes inclined downward, various other means of ventilating the wick were tried and in each case free water was still given off at the lower end of the flume.

A flume inclined downward at an angle of 15° and 20 feet long was filled with clear Santa Ana River sand. This sand contained practically no fine material and only traces of organic matter. Yet this flume, like the others described above, gave free water at the lower end of the flume, and within a week from the time the experiment was started.

It would seem, therefore, from the evidence of the ventilated wicks and flumes filled with types of soil from very coarse sand to fine clay and all giving off free water, that the capillary siphon, as above styled, is perfectly established.

It would also seem that capillary siphons occurring in nature might not be uncommon and that such siphons, first by capillarity alone, and later assisted by gravity, might cause the swamping of lands. Such a condition might arise if there were a stratum of soil of rather high capillary power and a rather impervious subsoil; if the upper end of such a soil arrangement were in contact with a body of water and the water did not have to be lifted too far by capillarity, and from that point the soil and subsoil had a slope downward at an angle

at least as great as 15°, then it would have the condition of the flumes above described. If, now, there were a sudden change in the slope of the ground toward the horizontal, or if the more loamy soil verged into a denser soil, free water might be developed at this point as the result of capillary action.

The capillary siphon might develop, also, in an earthen reservoir dam with a puddle or concrete core wall extending only to the flow line or slightly above it, and under certain conditions produce saturation in the lower side of the dam.

That a capillary siphon as above described is in accord with physical laws and was not the result of mechanical defects or error in manipulation is readily proven. Briggs (13) and Widtsoe and McLaughlin (19) have shown that the quantity of water retained by a soil column against gravity depends upon its length. Also that a column 1 foot in length will hold at all points a greater percentage of water than a column 2 feet in length. Hence, as the length of the inclined flume is greater, the percentage of moisture held against gravity will be smaller. It would follow, therefore, that beyond a certain length of the inclined part of the flume, not all of the water furnished by the wick could be retained against gravity by the inclined part of the flume.

It has been shown in this report that the distribution of moisture in vertical soil columns does not decrease uniformly with height above water. It has been indicated also that the greatest percentage of moisture in the vertical column may not be at the immediate water surface. From moisture analyses made of samples from vertical flumes, noted in this report, and from a great many other special experiments, the writer will say that the greatest percentage of moisture in a vertical soil column with its lower end in water may be and frequently is at an appreciable distance above the water. From these data and as the result of tests by the writer and others, it can be said that a vertical soil column can take up by capillarity from a body of free water more water than it can hold against gravity, if the free water be removed from the bottom of the soil column: that is, if the vertical tube is filled with soil and the lower end placed in a vessel of water and allowed to stand for a month or longer and the water is then removed from the tank, a part of the moisture in the soil column will drain out. To repeat—a vertical soil column will take up by capillarity from a body of water more moisture than it can retain when the source of the water is removed. In view of the above statements and the recorded experiments, it appears that capillary siphons may occur in nature, as the result of physical laws.

CAPILLARY MOVEMENT OF MOISTURE FROM A WET TO A DRY SOIL.

As has been stated previously, the movement of moisture by capillarity is much slower and not so extensive in the absence of free water as it is in the presence of free water. When a wet soil and a dry soil are in contact, gravity exerts an appreciable influence in the capillary movement of moisture.

The experimental work so far done at Riverside does not warrant more than a few general statements. To give some idea of the nature of this work a few experimental results will be given.

THE VERTICAL BOXES.

The soil boxes were placed in vertical and horizontal positions only. In the vertical boxes the wet soil was placed in some cases on top, in others at the bottom, and in others the wet soil was placed in the middle section and dry soils at both ends.

Nearly all boxes were 6 feet in length and the wet soil occupied one half this length and the dry soil the other half.

MOVEMENT OF MOISTURE UPWARD.

In table 43 are given data of a few of the boxes in which the soil moistened to the percentages shown were placed at the lower ends of

TABLE 43.—*Movement of moisture upward in the boxes.*

Days.	Riverside soil, initial percentage.		Idaho lava soil, initial percentage.			Whittier soil, initial percentage.	
	20 per cent.	10 per cent.	14 per cent.	20 per cent.	25 per cent.	40 per cent.	30 per cent.
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1	1.12			1.50			
2	2.25				1.00		
3	3.00	1.25	1.25				
4	3.37			2.25			
5	4.00						
6	4.50		1.83				
7	4.82	2.00					
8	5.00						
9	5.37			3.25	4.50		
11		2.25					
12			2.75				
14	7.00				6.50		
16				4.50			
23	8.87	4.37	3.25		7.75		
26						1.70	1.00
37	10.75		3.50	6.83			1.75
40					10.50		
49					11.00		
56	12.75						
71		6.50					
86					14.25		

the boxes and air-dried soils at the upper ends. The table shows that the box containing the Riverside soil, with the lower half 20 per cent of moisture, the movement of the moisture up into the dry soil was about one-fourth as great in 4 days as it was in 56 days. In the box of Riverside soil, containing 10 per cent moisture in the wet

pack, the movement of moisture into the dry soil the first 3 days was about one-fifth as great as in 71 days.

The other data in the table show the relatively rapid rate of moisture movement the first few days and the slowing down of the rate of movement with the lapse of time.

These results in connection with previous data for the flumes indicate that the larger part of capillary distribution of the water occurs while water is being applied and in the next two or three days thereafter.

The last two columns of the table, which give data for the heavy Whittier soil, show the very slow and limited capillary movement of moisture in this class of soils.

In the three boxes containing the Idaho lava-ash soil with relatively great capillary power, the movement of moisture up into the dry soil did not extend very far. In the box the wet pack of which contained 25 per cent of moisture the upward movement in 86 days was only 14.25 inches. The field capacity of this soil is from 20 to 25 per cent or a little less than the percentage of moisture in the box just considered.

In the box the wet pack of which contained 14 per cent of moisture the movement of the moisture upward was only 3½ inches in 37 days.

If the data in Table 43 were plotted as were the data for the flumes the resulting line would have a parabolic form.

MOVEMENT OF MOISTURE DOWNWARD.

Table 44 is arranged to show the distance the moisture moved downward in the boxes after various periods of time, the moist soils being placed above the air-dried soils. The table shows about the same conditions as did the previous table, except that the rate and extent of movement of the moisture downward are considerably greater than with the wet soils below the dry. The rate of movement downward is in proportion to the initial percentage of moisture contained in the wet soil.

In the Riverside soil containing 15 per cent of moisture, or about the field capacity, the extent of movement of the moisture at the end of the fourth day is approximately one-half the distance moved in 36 days. In the Idaho soil containing 20 per cent of moisture in the wet pack the moisture had moved in 36 days only about two and one-half times as far as it had at the end of 4 days. In the heavy Whittier soil the movement of the moisture even with a moisture content in the wet pack equal to or greater than the field capacity is very slow and does not move to any great distance in 30 days. The data of this table, if plotted, as were the other data, would give a curve resembling a parabola.

TABLE 44.—*Movement of moisture downward from wet soil.*

Days.	Riverside soil, initial percentage.		Idaho lava soil, initial percentage.			Whittier soil, initial percentage.	
	20 per cent.	15 per cent.	14 per cent.	20 per cent.	25 per cent.	41 per cent.	30 per cent.
	Inches.	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*	*Inches.*
1	4.50	4.00	0.75	2.00	3.00	...	...
2	...	5.75	...	...	5.25	...	...
3	7.50	6.37	...	...	...	...	...
4	...	7.00	...	4.75	...	...	...
5	...	...	1.75	5.00	...	...	...
7	...	...	...	...	9.00	...	...
8	11.75	8.50	...	...	...	...	...
9	...	...	4.00	8.00	...	...	...
13	14.00	9.50	...	...	12.00	...	...
16	15.75	10.75	4.50	8.50	...	...	...
22	17.25	11.25	...	...	15.25	...	...
27	...	12.00	...	...	...	...	...
31	21.50	...	...	...	16.25	2.25	2.00
36	...	14.25	...	11.50	17.25	...	...
41	...	15.00	...	...	...	...	...
43	25.50	...	...	...	...	...	...
49	...	16.25	...	12.75	...	...	...
71	...	...	...	...	21.50	...	...
76	...	...	...	...	22.25	...	...

COMPARISON OF CAPILLARY MOVEMENT OF MOISTURE UPWARD AND DOWNWARD FROM A BODY OF WET SOIL.

A series of experiments were outlined to determine the relative extent and rate of movement of moisture upward and downward from a body of soil containing a known percentage of moisture. In this experiment a section in the middle of the box was filled with wet soil and air-dried soil was packed at both ends. The box was then placed vertically. In this experiment the capillary movement occurred with gravity downward and in opposition to gravity. There was a secondary factor which must be considered, and that is the gradual concentration of moisture in a wet soil at the lower end of a vertical column due to gravity. That is, while the middle part of the flume was filled with a soil containing a uniform percentage of moisture it would be found after a few days, depending upon the degree of wetness of the soil, that there was a greater percentage of moisture near the bottom than near the top of the wet soil column. The more nearly the soil was wetted to the point of capillary saturation the greater would be the difference in percentage of moisture near the bottom and near the top.

Table 45 shows the upward and downward movement of moisture in two of the boxes.

The box containing the Idaho soil was 8 feet long and the middle 32 inches was packed with wet soil. There was an equal length of air-dry soil at each end.

The box containing the Riverside soil was 8 feet long and the middle 4 feet was packed with wet soil.

TABLE 45.—*Movement of moisture upward and downward, from soils containing an initial moisture content of 15 per cent.*

Time in days.	Idaho soil.			Riverside soil.		
	Distance moved.		Relation of up to down.	Distance moved.		Relation of up to down.
	Up.	Down.		Up.	Down.	
	Inches.	*Inches.*	*Per cent.*	*Inches.*	*Inches.*	*Per cent.*
2	1.50	....	....	2.25	3.50	64
4	1.50	2.25	67	....	....	....
5	....	....	....	2.62	7.25	36
6	2.30	3.20	73	2.88	7.75	37
10	....	....	....	3.75	10.00	37
13	3.00	4.50	67	....	....	....
17	....	....	....	5.75	13.00	44
23	4.12	5.50	75	....	....	....
31	4.50	6.75	67	....	....	....
36	4.80	7.00	68	6.50	18.25	35
43	....	....	....	6.75	19.00	36
52	5.37	8.37	64	....	....	....
71	6.00	9.12	66	....	....	....
76	6.25	9.24	67	....	....	....

Table 45 shows by percentage the relation of the upward movement of the moisture to the downward movement. After the first day or two the relation of the upward movement to the downward movement remains rather constant. The table shows the relative rapid rate of movement of moisture the first few days and the slower rate with the lapse of time. If the data in Tables 41 and 42 showing the upward and downward movement of moisture in separate flumes are compared, the same relative relation is found as found in Table 45.

The above data indicate the part gravity plays in soil-moisture distribution. Generally speaking, the lighter the soil the less is the upward movement of the moisture as compared with the downward movement. It also appears that the greater the percentage of moisture the greater the downward movement as compared with the upward.

The limited data above presented, when considered with many others in the original records, would lead to the conclusion that under irrigation much moisture may be carried below the root zone of plants, and that moisture once carried below the root zone of plants will probably not be again brought within the root zone in sufficient quantity to be of material benefit to the crop of that season, and hence will be lost to the plant.

THE MOVEMENT OF MOISTURE FROM WET TO DRY SOIL IN HORIZONTAL BOXES.

The capillary movement of soil moisture in a horizontal direction as found in the horizontal boxes is greater in extent than the upward movement in the vertical boxes, but not so great as the downward movement. There are given in Table 46 the results of three tests

with the Riverside soil, with 10, 15, and 20 per cent moisture in the wet soil. The table shows, like the preceding ones, that the rate and extent of movement of the moisture varies as the initial percentage of moisture in the wet pack. There is also shown the rapid moisture movement for the first few days and a slowing down of this rate with lapse of time. These data if plotted would also give a curve of a parabolic form. It is surprising to find so great an extent of movement of moisture in a horizontal direction when compared with the downward movements as shown in Table 42. If the difference in movement of moisture in the several boxes as representing the upward, downward, and horizontal can be attributed only to gravity, and this appears to be true, then gravity is a most important factor in the capillary distribution of soil moisture.

TABLE 46.—*Horizontal movement of soil moisture in Riverside soil.*

Time in days.	Initial moisture.		
	10 per cent.	15 per cent.	20 per cent.
	Inches.	*Inches.*	*Inches.*
1	0.75	4.00	5.75
2	1.25	5.50	7.00
3	1.50	6.25	8.25
4	....	....	9.25
5	1.83	7.50	9.75
7	....	....	10.75
10	3.00	9.50	....
12	....	....	13.50
16	5.00	11.00	15.00
19	5.25	....	....
21	....	....	16.25
24	....	13.25	....
29	....	....	17.75
40	5.50	18.25	19.50
46	....	....	23.25
49	....	19.00	....
51	....	....	23.50
54	....	19.25	....

While the experiments above noted are not sufficient in number to warrant any final conclusion, in connection with many others not contained in this report they indicate the probably distribution of moisture.

These data are in accord with results obtained by others (7), (9), (10), (18).

DISTRIBUTION OF MOISTURE IN BOXES CONTAINING WET AND DRY SOIL.

It is interesting to observe the distribution of the moisture throughout the entire length of the soil in the boxes at the termination of the experiments. It is interesting to observe the movement of moisture in quantity from the wet soil into the air-dried soil, and in the vertical boxes to note the relative percentages of moisture moved upward and downward. Table 47 gives the distribution of moisture at the end of the experiment in the soil boxes just previously discussed.

In Table 47 are given the kind of soil and the initial percentage of moisture contained in the wet soil as placed in the boxes at the beginning of the experiment. The percentages of moisture and the distances inclosed between the heavy lines in the body of the table show the original wet area of soil in the boxes and the remaining figures outside of the heavy lines show that part of the original air-dried soil with the corresponding percentages of moisture found at the end of the experiment. For instance, in the first two columns the first two lines indicated by minus 5 inches and minus 2 inches repre-

sent that part of the soil column immediately below the original wet soil area. Likewise the distances 34 inches and 40 inches at the bottom of the table represent that part of the original air-dried soil on top of the original wet soil. The other part of the table has a similar arrangement, except that the distances were taken from the bottom of the boxes. Referring to the Riverside soil it is found that the distribution of moisture from the bottom of the box upward is quite uniform until near the upper extremity of the original wet area. At a distance of 47 inches 9.19 per cent of moisture is found, while at 50 inches there is 6.6 per cent of moisture. In corresponding distances at the bottom of the box, represented by 22 inches and 18 inches, respectively, a much less variation in the percentage of moisture is found.

TABLE 47.—*Distribution of moisture by percentage in the soil boxes.*

Idaho soil, initial moisture 20 per cent.		Riverside soil, initial moisture 15 per cent.			
Distance.	Moisture content.	Distance.	Moisture content.	Distance.	Moisture content.
Inches.	*Per cent.*	*Inches.*	*Per cent.*	*Inches.*	*Per cent.*
−5	9.46	3	5.65	5	4.74
−2	11.31	6	7.08	8	6.90
2	14.09	9	8.25	11	8.05
6	14.46	12	8.61	15	8.81
12	15.05	15	9.09	19	9.04
18	16.00	18	9.42	22	8.75
24	15.44	22	10.79	24.5	11.40
28	15.51	25	10.20	27	12.37
31	15.40	26	10.34	30	11.28
34		31	10.60	34	11.50
40		34	10.00	38	11.05
		37	9.86	42	11.13
		40	9.38	46	10.45
		44	9.50	50	10.40
		47	9.19	54	9.35
		50	6.60	58	9.48
		58	3.90	62	9.43
				66	8.92
				70	8.28
				74	4.99
				77	3.28

It would seem from Table 47 that gravity has played its part in conjunction with capillarity in a rather uniform distribution of soil moisture from the wet soil area to the dry soil area. Upon the other hand it is found in taking the moisture percentages that gravity has very materially retarded the upward movement of the soil moisture. It is found, for instance, that the percentage of moisture found immediately below the original wet soil area is almost double the percentage of moisture found immediately above the upper end of the original wet soil area.

If such a condition as this maintains in the field, and there is no reason to believe it does not, then we can expect that capillarity and gravity will tend to a deep penetration of the moisture. The figures

in Table 47 and those immediately preceding show conclusively that capillarity and gravity tend to move the soil moisture downward to considerable depths and in about twice the quantity that the moisture moves upward. Add to this factor copious irrigation and it is readily seen how even capillarity can assist and does assist in the waste of irrigation water by deep penetration.

In none of the data presented just above has the original wet soil contained a percentage of moisture differing much from that which would be found in the field immediately following an irrigation.

Sufficient tests have not been made to warrant a final conclusion as to the ultimate importance of the deep penetration of moisture, by capillarity, in conjunction with gravity.

REFERENCES.

(1) ALWAY, F. J., and CLARK, V. J.
1912. A Study of the Movement of Water in a Uniform Soil under Agricultural Conditions. In Neb. Exp. Station, 25th Annual Report, p. 247–287.

(2) BANYANCOS, C. J.
1915. Effect of Temperature on Movement of Water Vapor and Capillary Moisture in Soils. Jour. Agri. Research, U. S. No. 4, p. 141.

(3) BRIGGS, L. J., and LAPHAM, M. H.
1902. Capillary Studies and Filtration of Clay from Soil Solutions, U. S. Dept. Agri., Bur. Soils Bul. 19, p. 14–24.

(4) BRIGGS, L. J., and MCLEAN, J. W.
1907. The Moisture Equivalent of Soils. U. S. Dept. Agri., Bur. Soils Bul. 45.

(5) BRIGGS, L. J.
1897. The Mechanics of Soil Moisture. U. S. Dept. Agr., Bur. Soils Bul. 10, p. 6.

(6) BUCKINGHAM, EDGAR.
1907. Studies on the Movement of Soil Moisture. U. S. Dept. Agr., Bur. Soils Bul. 38, p. 14.

(7) BURR, W. W.
The Storage and Use of Soil Moisture. Neb. Exp. Sta. Research Bul. 5.

(8) FREE, E. E.
Plant World, vol. 14, No. 2, p. 164.

(9) HARRIS, F. S.
1917. Soil Moisture Studies under Irrigation. Utah Exp. Station Bul. 159.

(10) 1917. Movement and Distribution of Moisture in the Soil. Jour. Agr. Research, vol. 10, No. 3.

(11) KING, F. H.
1899. Wis. Exp. Sta. 16th An. Report, p. 214.

(12) 1888. Soil Physics, Wis. Exp. Sta., 6th An. Report, p. 189.

(13) LOUGHRIDGE, R. H.
1894. The Capillary Rise of Water in Soils. Cal. Exp. Station, Report 1892–1894, p. 91.

(14) RISTER and WERY.
1904. Irrigation et Drainage, p. 66, Paris.

(15) SMITH, ALBERT.
1917. Relation of the Mechanical Analysis of the Moisture Equivalent of Soil. Soil Science, vol. 14, No. 6, p. 471.

(16) STEINMETZ, CHARLES P.
1917. Engineering Mathematics, New York.

(17) WIDTSOE, J. A.
1914. Principles of Irrigation Practice, p. 17. New York.

(18) WIDTSOE, J. A. and MCLAUGHLIN, W. W.
1902. Irrigation Investigations in 1901. Utah Exp. Sta. Bul. 80.

(19) 1912. The Movement of Water in Irrigated Soils. Utah Exp. Sta. Bul. 115.

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